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published in
Journal of Experimental Psychology: Human Perception and Performance
2017

DOI (link to publisher)
10.1037/xhp0000465

document version
Peer reviewed version

Title

Visual strategies underpinning the development of visual-motor expertise when hitting a ball

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Word count: 15,333

Abstract

It is well known that skilled batters in fast-ball sports do not align their gaze with the ball throughout ball-flight, but instead adopt a unique sequence of eye and head movements that contribute towards their skill. However, much of what we know about visual-motor behaviour in hitting is based on studies that have employed case-study designs, and/or used simplified tasks that fall short of replicating the spatio-temporal demands experienced in the natural environment. The aim of this study was to provide a comprehensive examination of the eye and head movement strategies that underpin the development of visual-motor expertise when intercepting a fast-moving target. Eye and head movements were examined in-situ for four groups of cricket batters, who were crossed for playing level (elite or club) and age (U19 or adult), when hitting balls that followed either straight or curving ('swinging') trajectories. The results provide support for some widely cited markers of expertise in batting, while questioning the legitimacy of others. Swinging trajectories alter the visual-motor behaviour of all batters, though in large part because of the uncertainty generated by the *possibility* of a variation in trajectory rather than any actual change in trajectory per se. Moreover, curving trajectories influence visual-motor behaviour in a non-linear fashion, with targets that curve away from the observer influencing behaviour more than those that curve inwards. The findings provide a more comprehensive understanding of the development of visual-motor expertise in interception.

Keywords: interception; gaze; curvilinear; cricket; vision.

Public significance statements

- In fast-ball sports such as baseball and cricket, skilled batters do not 'watch the ball' throughout its ball-flight, but rather use a unique sequence of eye and head movements to predict where the ball is heading towards.
- Ball-flight trajectories that curve through the air (such as 'curveballs' in baseball, and 'swinging deliveries' in cricket) profoundly impact performance and alter the ability of batters to track the ball with their eyes.

Introduction

The successful interception of a moving target can demand an extraordinary degree of visual-motor coordination (Tresilian, 2005; Warren, 1988). Hitting tasks in fast-ball sports (such as baseball, hockey and cricket) are often used as a model to better understand the strategies that underpin interception because the highly demanding spatio-temporal constraints in these tasks often test the limit of human achievement (Regan, 1992, 1997; Walsh, 2014). Empirical studies of the unique sequence of eye movements that skilled performers rely on during interception have revealed fascinating insights that have been very influential in improving our theoretical understanding of how interceptive actions are controlled and performed (e.g., Land & McLeod, 2000; Mann, Abernethy, & Farrow, 2010; Ripoll & Fleurance, 1988; Ripoll, Fleurance, & Caseneuve, 1987). However, the conclusions made by these studies have generally been based on case-study designs that rely on a low number of participants. Given the present concerns about replication in science (Open Science Collaboration, 2015), it remains unclear how representative these results are of the wider population (Sarpeshkar & Mann, 2011). Moreover, most existing studies have used relatively simplified task designs (for instance using predictable and/or rectilinear target trajectories; e.g., Croft, Button, & Dicks, 2010; Land & McLeod, 2000; Mann, Spratford, & Abernethy, 2013) that probably facilitate prediction, and therefore fall short of faithfully replicating the actual task demands they seek to represent (Pinder, Davids, Renshaw, & Araújo, 2011; Pinder, Renshaw, & Davids, 2009). As a result, there remains considerable uncertainty about whether the findings from these studies provide an accurate representation of skill in the natural environment.

When performing a fast-paced interceptive task, hitters in fast ball sports do not follow the common coaching adage to '*keep your eyes on the ball*' (e.g., Bahill & LaRitz, 1984; Land & McLeod, 2000; Mann, et al., 2013). Instead, batters appear to exploit a strategic combination of information from central and peripheral vision to track the target throughout its flight-path (Bahill & LaRitz, 1984; Land & McLeod, 2000). In their classic study published in Nature Neuroscience, Land and McLeod (2000) demonstrated that cricket batters rapidly shift their central vision ahead of the target to predict its future location. Following ball-release, cricket batters were found to track the ball for the initial portion of its flight before performing an *anticipatory saccade* that moves gaze towards the predicted location of ball-bounce. Crucially, when compared to lesser-skilled batters Land and McLeod reported that skilled batters perform *earlier* saccades, helping to explain their superiority in batting. The capacity of the skilled batters for better prediction has been said to be consistent with the idea that skilled batters develop an internal model of ball-flight to predict where the ball will be in the near future, and to position gaze in anticipation of a predicted event such as ball-bounce (Diaz, Cooper, Rothkopf, & Hayhoe, 2013; Land & Furneaux, 1997).

A recent study by Mann, et al. (2013) examined the gaze behaviour of two of the world's best cricket batters, raising two additional findings which help to further our understanding of visual-motor expertise in batting. First, the elite batters used their eyes to guide their head so that the head was directed towards the position of the ball throughout the majority of its flight. In other words, the batters moved their head in a fashion that ensured the position of the ball was largely retained within a single egocentric direction relative to the head. Mann et al. hypothesised that batters could use this strategy to help predict the direction in which the ball would arrive (relative to the head). If the batter is able to maintain the ball within a consistent egocentric direction throughout its ball-flight, then the batter will have isolated the precise direction in which the ball will arrive, thereby simplifying the interceptive task to one where only time-to-contact would be needed to hit the ball (see Lee, Young, Reddish, Lough, & Clayton, 1983; Oudejans, Michaels, Bakker, & Davids, 1999; Savelsbergh, Whiting, & Bootsma, 1991). Second, the batters produced anticipatory saccades not only towards the location of ball-bounce, but also often produced a second anticipatory saccade towards the location of bat-ball contact. Land and McLeod (2000) had reported that after ball-bounce, batters attempt to track the ball, but generally are unable to do so in the final moments leading up to bat-ball contact. In contrast, Mann, et al. (2013) found that all of the batters they tested were able to perform a second anticipatory saccade to the location of bat-ball contact, though the ability to do so depended on where the ball bounced. Each of the batters could produce an additional saccade to watch the ball hit the bat when the ball bounced far away from them (a 'short' length trial), but it was only the elite batters who could consistently watch the ball at bat-ball contact in the trials that bounced closer to them ('good' or 'full' length trials when there was less time to react after bounce). The elite batters did so either by producing a second saccade, or by tracking the ball up to the moment of contact. Essentially, the elite batters appeared to be doing whatever was necessary to direct their gaze towards the predicted location of contact. Mann et al. proposed that the ability to direct gaze towards contact could allow batters to monitor the path of the ball with their peripheral vision, helping them to make adjustments to their bat-swing as late as is permissible by the sensorimotor system (Bootsma & van Wieringen, 1990; Ripoll & Fleurance, 1988). By doing so, the truly elite performers may have developed a simple, yet elegant means by which to alter their actions as late as they possibly can (also see Lee, et al., 1983; Ripoll & Fleurance, 1988).

Collectively, the findings from these and other studies of gaze behaviour (e.g., Diaz, Cooper, & Hayhoe, 2013; Panchuk & Vickers, 2006; Ripoll & Fleurance, 1988; Ripoll, et al., 1987) have laid the foundation for our present understanding of the visual strategies that underpin successful interception. However, these conclusions about skill-related differences in gaze have commonly been made on the basis of very low sample sizes. For instance, Land and McLeod (2000) examined just three batters, each of a different skill level (provincial, amateur or recreational), and Mann et al. (2013) tested four batters of two different skill levels (two international and two club-level). As a result, it is unclear whether their findings are truly representative of those expected across the wider population.

A second fundamental concern about many of the existing studies of visual-motor behaviour is that they typically examine performance in tasks that are simplified and do not necessarily replicate the constraints experienced during competition. For instance, Croft, Button and Dicks (2010) examined the gaze behaviour of cricket batters who faced balls that followed only one single ball trajectory, thereby making the ball-flight very predictable. Similarly, Land and McLeod (2000) examined gaze behaviour when batters faced balls that (i) were projected from a ball-machine rather than a bowler, providing a-priori information about the likely direction of the ball (Renshaw, Oldham, Davids, & Golds, 2007), and (ii) travelled at a ball-velocity that was considerably slower than that usually experienced during competition (25 $m.s^{-1}$ [90 $km.h^{-1}$] rather than the ≈42 $m.s^{-1}$ [150 $km.h^{-1}$] common in international competition). The predictable nature of these designs represents a pertinent concern, particularly given that these studies generally conclude that expert performers have a significant advantage in the nature of their anticipatory (predictive) behaviour. Indeed, a baseball pitcher would rarely pitch for example only fastballs; instead they rely on a variety of pitches, and skilled batters must develop strategies to account for this variability (Cañal-

Bruland, Filius, & Oudejans, 2015; Gray, 2002, 2009). Similarly in cricket, a bowler will attempt to employ more complex ball-flight trajectories (by imparting swing or spin) to minimise the batter's ability to make predictions about the likely trajectory. Given the assumed importance of anticipatory behaviour in hitting (Abernethy, 1981; Land & McLeod, 2000), it is clear that task designs are required which are less predictable and therefore can capture the true essence of expertise seen during competition.

One common way that athletes in fast-ball sports seek to impair the predictive ability of opponents is through the use of *curvilinear* or *curving* trajectories, for example when a baseball pitcher throws a curveball, or a football penalty taker bends the ball through the air. Curvilinear trajectories arise as a result of a pressure differential created by an imbalance in the airflow around an object that is either spinning (e.g., for a curving football), or has contrasting surface textures (such as the shiny and rough sides of a swinging cricket ball; for a comprehensive overview, see Mehta, 2008). This pressure differential generates an additional force perpendicular to the object's flight-path, causing it to deviate laterally in the direction of lower pressure (i.e., Magnus forces; for more information, see Mehta, 2005, 2008). In cricket and baseball, this often leads teams to manipulate the surface of the ball (sometimes unlawfully, see Mehta, 2005; Moonda, 2016) to alter the ball-flight characteristics and maximise the chance that the ball will 'swing'.

In fast ball-sports, interceptive performance decreases substantially when a target follows a curving rather than a linear trajectory (Craig, Bastin, & Montagne, 2011; Craig et al., 2009; Port, Lee, Dassonville, & Georgopoulos, 1997). Craig, et al. (2011) examined the interceptive performance of recreational football goalkeepers who attempted to stop kicks in a virtual environment, finding a surprisingly large decrease in success rate when intercepting a curving rather than straight trajectory (15 vs. 57% respectively). Similarly, we have recently shown (Sarpeshkar, Mann, Spratford, & Abernethy, 2017) that it is much more difficult for cricket batters to intercept a curving trajectory than it is a straight trajectory in-situ (success rate = 49 vs. 71%).

When compared to straight trajectories, a critical distinction required when intercepting curving trajectories is that the observer needs to account for a continuous lateral deviation in flight-path to predict the future location of the target. In other words, the instantaneous direction of the target is constantly changing, and therefore this must be taken into account in order to anticipate where the target will arrive (see also Bootsma, Ledouit, Casanova, & Zaal, 2016; Casanova, Borg, & Bootsma, 2015; Montagne, Laurent, Durey, & Bootsma, 1999; Peper, Bootsma, Mestre, & Bakker, 1994). This has led to the conclusion that the informational variables that would typically allow performers to accurately predict where a target will arrive may be less reliable when the target follows a curving trajectory, and therefore that there may be a fundamental limitation within the visual system that restricts the observer's ability to account for the continually changing trajectory of a curving target (Craig, Berton, Rao, Fernandez, & Bootsma, 2006; Craig, et al., 2009; Port, et al., 1997).

Given that a curvilinear flight-path decreases interceptive performance, and may be associated with a limitation in the ability to make predictions about its future location, it seems reasonable to also expect more 'novice-like' gaze behaviour when batters attempt to intercept curving trajectories. In essence, we might expect gaze to be *less predictive*. One particular way to examine the nature of predictions in the presence of a curving flight-path is through an examination of anticipatory saccades. Potential markers of poorer prediction would be fewer anticipatory saccades, and/or a delay in when those saccades are initiated. Conversely, if batters could make predictions that did account for lateral deviations in ball-flight, then we might expect them to produce *oblique saccades*. Instead of simply moving gaze forward along a straight vector that is continuous with the instantaneous direction of the ball, an oblique saccade will incorporate an additional *lateral* component perpendicular to that vector to account for the constant change in direction inherent when the ball follows a curving trajectory. Mrotek and Soechting (2007) have previously shown that oblique saccades are sometimes produced when a section of a curving target's trajectory is occluded, helping to account for the target's lateral movement (see also Smit, Van Opstal, & Van Gisbergen, 1990; Viviani, Berthoz, & Tracey, 1977). Although this behaviour has not yet been reported when intercepting a target *in situ*, oblique saccades might be expected if batters are able to make predictions that account for the change in direction of the target. Given their expertise in batting, skilled batters might be better able to make use of oblique saccades to account for the trajectory of a curving flight-path. In contrast, a visual strategy that does not account for the lateral deviation in ball-flight would result in straight saccades that incorrectly anticipate where the ball is directed, and could be associated with a misperception of the position of the ball (including the common report by baseball batters of the 'sudden' break of a curveball; for more information, see Bahill & Baldwin, 2004; Shapiro, Lu, Huang, Knight, & Ennis, 2010; Sivak & MacKenzie, 1992).

Finally, in some tasks we might expect the *direction* of curvature to significantly influence the ability of batters to make predictions about ball-flight. In some situations, the observer intercepting the target will stand directly opposite their opponent (for instance a football goalkeeper stopping a penalty), and so the direction of curvature (to the right or left) should not influence interception because the perceptual information is mirrored (e.g., Lenoir, Vansteenkiste, Vermeulen, & De Clercq, 2005). An asymmetry exists though in other scenarios, as is the case for a baseball (or cricket) batter who stands to one side of the home plate (or stumps). In that case the perceptual information may no longer be mirrored, resulting in an asymmetry in the flight-path of a target that swings ‘in’ or ‘away’ from the observer’s line of sight (in-swing and out-swing respectively, see Figure 1A). The ability to estimate where a target will pass in the future can be significantly altered by the angle of approach of a target (Montagne et al., 1999; Peper et al., 1994), and given that the angle of approach will differ for a target that curves in or away, then it stands to reason that performance could differ for the different trajectories. We have recently shown that a curving trajectory which moves away from the body is much more difficult to intercept than one which moves in towards the body (Sarpeshkar, et al., 2017), possibly because the change in heading direction in the early portion of ball flight is more obvious for the trajectory that moves in towards the body (Peper, et al., 1994). In contrast, the initial direction of the target that moves away is more likely to be aligned with the batter’s eyes and head (because it travels along the batter’s line-of-sight) for the majority of ball-flight, potentially making it more difficult to detect both the approach angle of the ball (Welchman, Tuck, & Harris, 2004), and the rate of lateral deviation (Diaz, Phillips, & Fajen, 2009). If informational variables are more difficult to pick-up in one particular direction of curvature (e.g., for a trajectory that curves away), then it seems reasonable to expect more novice-like gaze behaviour on those trials, again with less predictive behaviour.

The aim of this study was to comprehensively examine the eye and head movement strategies that underpin the development of visual-motor expertise when performing a fast-paced interceptive action. The eye and head movements of four groups of cricket batters, who systematically differed in their level of batting skill and/or age, were examined when hitting balls that were presented in (i) a block of straight trajectories only (*blocked-straight* trials), and (ii) a combination of straight and swinging trajectories (*random-straight* along with *out-swing* and *in-swing* trials). We separated the analysis into four sections that each addresses a specific comparison. In Section I we examine visual-motor behaviour when batters intercept the blocked-straight trials to determine whether the markers of visual-motor skill reported in previous case-studies can be replicated in a larger sample. If so, then consistent with the previous literature, we expected that elite batters would demonstrate more predictive gaze behaviour (earlier and more frequent predictive saccades when batting) and better egocentric head-tracking of the ball. In Section II, we compare the blocked-straight and random-straight trials (the straight trials mixed with swinging trials) to establish whether the *possibility* of changes in ball trajectory (in this case ball-swing) alters visual-motor behaviour, even when facing straight trials. We hypothesized that, if the uncertainty generated by the possibility of ball-swing influences the ability to make predictions about the future location of the ball, then when the ball *could* swing we would observe gaze behaviour that is *less* predictive (i.e., later and less frequent saccades). Moreover, we expected that any effect of uncertainty about ball-flight would be less pronounced for more skilled batters because they would have developed specific strategies to overcome these variations in ball-flight (Cañal-Bruland, et al., 2015). In Section III, we compare the random-straight and swinging trials to determine whether there are changes in visual-motor behaviour. Given the marked decrease in interceptive performance typically found when intercepting curving trajectories (Craig, et al., 2009; Sarpeshkar, et al., 2017), we expected to find more 'novice-like' gaze behaviour when the ball did swing (i.e., less predictive gaze and poorer head tracking). Again, we expected any change in behaviour to be less pronounced in the more skilled batters. Finally, in Section IV we compare the out-swing and in-swing trials to establish whether the direction of swing alters visual-motor behaviour. Given that trajectories which swing away from the body are more difficult to intercept (Sarpeshkar, et al., 2017), we expected to find less predictive gaze behaviour when intercepting those trials, particularly in the less-skilled batters.

Method

Participants

A total of 43 male cricket batters took part in the study. Batters were categorised into one of four groups that were crossed according to their level of batting skill (*elite* or *club*) and age (*adult* or *youth*). The *adult elite* group (13 batters, M_{age} = 25.1 years) consisted of batters who had all represented their state or country at a senior level (including four members of the Australian national squad). The *youth elite* group (10 batters, M_{age} = 17.7 years) had all represented their state or country at an under-19 and/or under-17 level (including four members of the Australian under-19s national squad). The *adult club* (10 batters, M_{age} = 31.7 years) and *youth club* groups (10 batters, M_{age} = 21 years) consisted of lesser-skilled recreational batters who played competitive club cricket in a local district competition and had not achieved any higher level of representative selection.[1] Our original plan was to recruit ten participants in each group, however three extra adult elite batters were available at the time of testing, so we decided to include their data in the study prior to the commencement of any analysis. Prior to taking part in the study, all batters provided informed consent to a protocol that was approved by the University ethics committee.

Experimental Design

The study took place at an indoor facility which replicated the dimensions and ball-rebound characteristics of a synthetic cricket surface. A ProBatter ball-projection machine (PX-2-PB2005-87; ProBatter Sports, Milford, CT) was used to project balls towards the batters. The ProBatter incorporates a life-sized video projection of a bowler shown on a screen (2.6 m x 3.5 m) that is synchronised with the ball machine, ensuring that a ball is projected through a hole in the screen at the moment the ball would be released by the bowler seen in the video footage (see Portus & Farrow, 2011; ProBatter Sports, 2015). A series of different video recordings of a particular bowler (recorded live during competition) was edited and programmed so that the ball-flight seen for that delivery was matched as closely as possible to that actually

[1] The adult batters were significantly older than the junior batters (M_{age} = 28.0 ± 6.8 vs. 19.4 ± 2.1 years; $t(41)=5.4$, $p<.0001$, $d=1.7$), permitting the comparison of performance across the age groups. However, it was difficult to balance the age of the two adult groups (senior vs. youth) and two club groups (senior vs. youth), suggesting caution is required for the interpretation of any skill x age interactions.

bowled in the video footage, maximising the chance that the kinematic information available from the bowler's action matched the actual ball flight (for the benefits of the ProBatter machine over a live bowler or bowling machine, see Mann, et al., 2013). The ProBatter was designed so that the dimensions replicated those typically experienced during competition, specifically, the distance from the screen (and therefore location of ball release) to the stumps located behind the batter (18.9 m), the height of ball-release from the ground (2.08 m), and the approach angle of the ball towards the batter (bearing angle of ≈2°). At the moment of ball-release, a ball commonly used during training, and designed to act like a cricket ball (Jugs Inc., Tualatin, Oregon), was projected through a hole in the screen at a velocity of ≈33 $m.s^{-1}$ (119 $km.h^{-1}$). This ball-speed was chosen to be representative of what would be encountered in competition, but one which would also be safe for all participants. Batters used their own cricket equipment (i.e., leg and thigh guards, gloves and cricket bat), and were instructed to bat as they would during competition, that is, in a manner that would allow them to score runs whilst minimising the likelihood of being dismissed.

Prior to data collection, three distinct areas on the playing surface were selected (i.e., '*lengths*') to represent the different locations of ball-bounce relative to the stumps located behind the batter (*viz*. *full*, *good*, and *short* length trials; the batter stands ≈1 m in front of the stumps). In the full-length trials (or *deliveries*), the ball bounced between 3.5-4.5 m from the stumps (M = 4.1 m, SD = 0.3), a bounce position that would typically require the batter to step *forward* to hit the ball. Good-length trials bounced between 7-8 m from the stumps (M = 7.8 m, SD = 0.2). This ball-length is commonly considered to be the most challenging bounce position from which to hit the ball, because it typically causes indecision as to whether to step forward or backward to hit the ball. Short-length trials bounced between 8.5-9.5 m from the stumps (M = 9.1 m, SD = 0.2), typically requiring the batter to step *backward* to hit the ball. The variations in length served two specific purposes. First, they ensured there was variation in ball-flight between trials, minimising the likelihood of batters being able to predict the trajectory of upcoming trials. Second, the magnitude of any skill-related differences in gaze behaviour during interception typically differ according to ball-length (Mann, et al., 2013), with differences most apparent against good and to a lesser-extent the full-length trials, and least apparent against short-length trials. The arrival location of the ball was also manipulated according to one of two different *lines*, resulting in trials where the ball arrived either close to, or away from, the batter's body. These variations in line only served to further prevent the batter from anticipating the future location of the ball, and were of no experimental interest.

Trials could either follow a rectilinear (*straight*) or curving (*swinging*) trajectory. To achieve ball-swing, sideward spin was imparted on the ball to ensure that the ball swung either in towards (*in-swing*), or away from (*out-swing*) the batter's body (Figure 1A).

Data Collection

Participants wore a *Mobile Eye* monocular eye tracking system (25 Hz; Applied Science Laboratories, Bedford, MA) to record the direction of gaze while batting. The Mobile Eye footage was recorded on a portable video recording unit (Sony GV-D 1000 MiniDV Video Walkman, ≈1 kg) that was housed in a pouch worn around the batter's waist. To ensure that any disturbances to the camera were detected and corrected for, a radio transmitter was also connected to the recording unit to wirelessly transmit the video footage to an LCD television screen located adjacent to the test area. Batters wore a customised helmet that had a portion of the brim removed to allow sufficient space for the eye tracking camera. Calibration of the eye tracker was performed, while the batter adopted their usual batting stance, using four predetermined locations in the visual field (the position of ball release, the bottom left and right corners of the projection screen, and a specific point on the projector located on the ground in front of the batter). Recalibration of the eye tracker was performed prior to, and after the completion of each condition, or if the unit was disturbed. A separate video camera (Sony HDR-FX 1000, Tokyo, Japan; 25 Hz) was also positioned behind the batter to be used for the synchronisation of the eye-movement footage with the moment of ball-release, ball-bounce, and/or bat-ball contact when any of these events were not clearly visible in the Mobile eye footage.

Procedure

Prior to data collection, batters were allowed a short warm-up (≈10-15 deliveries) to familiarise themselves with the ProBatter machine, the Mobile eye, and the type of trials they would experience in the experiment. The ProBatter machine was new when used, and therefore the batters had little or no experience against it or any other similar type of machine. During the experiment proper, participants faced two blocks of trials, with the order of presentation of those blocks counterbalanced across participants: a block of (i) straight trials only, and (ii) a combination of straight and swinging trials. In the straight only (*blocked-straight*) trials, participants faced 18 trials that followed a straight flight-path, and were equally distributed across the three different ball-lengths and two lines (but were presented in the same randomised order for each participant). In the other block, participants faced a mixture of straight (*random-straight*) and *swinging* deliveries. This block consisted of 48 trials: 16 straight trials, 16 out-swing trials, and 16 in-swing trials. Trials were evenly distributed across the two lines, but only two different ball-lengths were used (full and good-length), because the ProBatter machine could not project short-length deliveries while imparting swing. The straight, out-swing, and in-swing trials were mixed together and presented in the same randomised order for each participant. Although the order of the trials within each block followed the same randomised sequence, the trial on which that sequence commenced was selected randomly for each batter (the ProBatter could not randomise the order of presentation of the trials within the sequence, but it could randomise the trial on which it commenced). Each batter took approximately one hour to complete the study.

Data Analysis

Footage from the Mobile Eye was digitised manually (Kinovea 8.15, 2011) to obtain, for each video frame from the moment of ball-release to bat-ball contact, the x-y coordinates of five specific locations in the visual field: the (i) location of gaze; (ii) location of ball-release; (iii) ball; (iv) bottom left, and (v) bottom right of the projection screen. The first three reference points allowed for the calculation of the raw gaze, head, and ball angles subtended at the eye (in degrees). The scene camera of the Mobile Eye moved commensurate with movement of the batter's head, ensuring that any movement of a fixed location, such as the location of ball-release, provided a direct measure of head movement. The three raw angles were used to calculate three relative angles: (i) the *gaze-ball angle*, (ii) the *gaze-head angle*, and (iii) the *head-ball angle* (see Figure 1B). Because the vertical and horizontal axes seen in the Mobile eye footage were unlikely to align with the corresponding global vertical and horizontal axes (because of sideways head rotation), the coordinates of the bottom left and bottom right of the projection screen were used as a reference for the global horizontal to correct the angles so that they were reported in a global rather than local (head-based) coordinate system. The x-y coordinates for the five spatial locations for a single participant showed high levels of intra- and inter-tester reliability (98% and 96% agreement respectively; intra-tester coding performed four weeks apart).

Additionally, the eye movement footage was viewed frame-by-frame to record the type and timing of any saccades that took place between the moment of ball-release and bat-ball contact. A saccade was recorded when a distinctive shift in gaze occurred that was not commensurate with the flight-path of the ball. Three types of saccades were recorded: (i) a *saccade towards ball-bounce*, where there was a visible change in the rate of movement of gaze that was quicker than the flight-path of the ball, was initiated *prior* to ball-bounce, and brought gaze ahead of the ball to a stationary position at the position of ball-bounce; (ii) an *oblique saccade towards ball-bounce* was the same as a regular saccade to ball-bounce, with the exception that the saccade incorporated a *lateral* movement perpendicular to the heading direction of the ball (the oblique saccades to ball-bounce form a subset of all regular saccades to ball-bounce); and (iii) a *saccade towards bat-ball contact*, where there was a visible change in the rate of movement of gaze that was quicker than the flight-path of the ball, was initiated *after* ball-bounce, and that brought gaze ahead of the ball to a stationary position towards the future position of bat-ball contact. The type and timing of the saccades were independently assessed by two trained researchers for one batter from each of the four groups, revealing a high degree of intra- and inter-tester reliability (minimum 97% and 81% agreement respectively). Pilot testing revealed that it was only possible to reliably identify oblique saccades towards ball-bounce (and not towards bat-ball contact), because the ball-velocity and frame rate of the Mobile Eye camera made it difficult to accurately determine the lateral gaze position when the ball was close to the batter. Batters also performed other types of saccades that either caught up with, or took gaze ahead of the ball during flight. Although an attempt was made to sub-categorise these saccades, inter-tester reliability proved to be poor for these saccades, therefore we did not include them in our analyses.

Dependent Variables. A series of dependent variables were assessed to examine the (a) batting performance, (b) relative positions of gaze, head and ball throughout ball-flight, (c) type and timing of saccades, and (d) gaze position at the moment of bat-ball contact.

(a). Batting performance: Two measures of interceptive performance were assessed in real-time: (i) the *quality of bat-ball contact* (QoC; Müller & Abernethy, 2008), and (ii) the *forcefulness of bat-swing* (FoBS; Mann, et al., 2010). The QoC is a simple and validated categorical measure used to determine whether the batter successfully made contact with the ball. A score of two, one, or zero is given for each trial to represent good, poor or no contact respectively. 'Good' contact indicates that the ball, after being hit, travelled in a direction consistent with the plane of motion of the bat; 'poor' contact indicates that the ball was hit, but moved in a direction *inconsistent* with the plane of motion of the bat (indicating that it hit the side rather than the centre of the bat); and 'no' contact indicates that the bat did not make contact with the ball (Müller & Abernethy, 2008). The score for the QoC was used to calculate the *% of trials with 'good' bat-ball contact* (Müller & Abernethy, 2006; Sarpeshkar, et al., 2017). The FoBS provides a categorical means of assessing how hard the ball is hit, reflecting the likelihood of runs being scored by the batter. A more aggressive bat-swing requires greater spatio-temporal precision, because there is a decrease in the time window in which the bat is optimally positioned to hit the ball. A score of two, one, or zero is given for each trial to respectively reflect (i) a complete follow-through of the bat after the anticipated point of bat-ball contact, (ii) a partial follow-though, or (iii) either no follow-though or no bat-swing at all (Mann, et al., 2010). This allowed the calculation of the *% of trials with high FoBS,* specifically, the percentage of trials with a FoBS score of two, to determine the extent to which the nature of the bat-swing changed across the different experimental conditions.

(b) Relative positions of gaze, head and ball throughout ball-flight: The mean and the standard deviation of the (i) *gaze-ball*, (ii) *gaze-head*, and (iii) *head-ball* angles were calculated in degrees in both the vertical and lateral directions for each trial (a negative value reflects the first term being respectively directed downwards or to the left of the second term). The proportion of ball-flight where batters directed their gaze ahead the ball (*% $Gaze_{ahead}$*) was also calculated.

(c) Type and timing of saccades: The frequency of each of the three types of saccade was reported as the percentage of trials in which that type of saccade was performed, with the timing of each type of saccade reported relative to the moment of ball-release (as the *mean ± standard deviation* in ms).

(d) Gaze at bat-ball contact: To determine whether gaze was directed towards the ball at contact, video footage of the moment closest to contact was manually viewed in conjunction with the frames prior to and after contact. Gaze was judged to have been directed towards the ball at contact if it was within one bat-width of the location of bat-ball contact (approximating 4 deg of visual angle). Although it is difficult to conclusively establish whether the fovea was directed towards the ball at the moment of contact, this approach does allow for the differentiation between gaze being directed towards bat-ball contact, as opposed to when gaze was clearly directed elsewhere (usually lagging behind the ball, or directed towards where the ball will be hit; Mann, et al., 2013). This allowed us to calculate the percentage of trials in which gaze, at the moment of bat-ball contact, was either: (i) co-located with the ball ($\% \ BBC_{contact}$), (ii) lagging behind the ball ($\% \ BBC_{lagging}$), or (iii) directed to where the ball would be hit ($\% \ BBC_{post\text{-}contact}$). The manual coding of the location of gaze at the moment of bat-ball contact revealed high levels of intra- and inter-tester reliability (98% and 90% respectively).

Section I: Differences in Visual-Motor Behaviour when Batting as a Function of Skill and Age

Some of the most influential conclusions about visual-motor behaviour in fast-ball sports come from studies that employ case-study designs, and it remains unknown how representative those findings might be of the wider population. Therefore, the aim of Section I was to provide a comprehensive examination of the eye and head movements of batters of different skill levels and age when performing a fast-paced interceptive action. If the findings of previous work were to generalise more widely, then it was expected that elite batters, when compared to lesser-skilled batters, would demonstrate (i) better batting performance, (ii) earlier saccades towards ball-bounce (Land & McLeod, 2000), (iii) more saccades towards bat-ball contact (Mann, et al., 2013), (iv) gaze co-located with the ball at bat-ball contact (Mann, et al., 2013), and (v) better egocentric head tracking of the ball (Mann, et al., 2013). We were also interested in investigating whether the *age* of the batters would alter the magnitude of the differences in visual-motor behaviour between elite and club batters. While most studies examine behaviour in adult batters, others have recruited adolescents (e.g., Croft, et al., 2010), presumably acting under the assumption that the expert-like gaze behaviour present in adults would be apparent during adolescence. However, there is conjecture about the age at which anticipatory behaviour develops in interceptive tasks: Tenenbaum, Sar-El, and Bar-Eli (2000) reported that the ability of tennis players to predict the future location of the ball is evident as early as 8-11 years of age (using the temporal occlusion paradigm); while Weissensteiner, Abernethy, Farrow, and Müller (2008) found that anticipatory skill in cricket batting may only necessarily develop in late adolescence (beyond 17 years of age). If skill-based differences in gaze are acquired during adulthood, then we expected to find more pronounced differences in visual-motor behaviour between the adult elite and adult club batters than we would between the youth elite and youth club batters (Weissensteiner, et al., 2008). This would indicate that the accumulation of experience and/or maturation may be necessary for the development of expert-like gaze behaviour (see Côté & Hay, 2002). In contrast, if advantageous visual-motor behaviour were to fully develop prior to adulthood then the magnitude of the differences between the elite and club batters should not differ between the adult and youth batters. If true, then visual-motor behaviour could act as a useful marker for talent identification in young batters.

Analysis

In order to compare our results to those reported previously, the analysis for Section I was limited to the blocked-straight set of trials where batters knew that they would be intercepting trials that followed only a straight trajectory. A total of 543 out of 774 possible blocked-straight trials (70%) were included for analysis: 169 trials for the adult elite group, 126 for the youth elite, 118 for the adult club, and 130 for the youth club. In sum, 177 trials were excluded because the batter did not swing their bat to hit the ball (23% of all trials; gaze generally ceases to track the ball when this occurs), and 54 trials were excluded because the Mobile eye failed to reliably obtain the location of gaze for more than two consecutive frames (7% of trials).

For each dependent variable, the mean value for each batter was first calculated across trials before being subject to statistical testing. We used two different statistical approaches to analyse the findings. First, each dependent variable was subject to ANOVA testing using a 2 (Skill: elite, club) x 2 (Age: adult, youth) x 3 (Ball-length: full, good, short) ANOVA with repeated measures on the last factor. The use of multiple ANOVA tests does run the risk of Type I error, but was used to ensure that our testing was sensitive enough to detect effects reported previously. Second, to provide a more conservative interpretation, we analysed the same data using stepwise discriminant function analyses (DFA) to determine the variables that best predicted membership for the batter's skill level, and for their age group (Weissensteiner, et al., 2008). For each DFA, a multivariate analysis of variance (MANOVA) was first performed that incorporated each of the dependent variables. Variables found to be significant within the MANOVA were subject to the DFA using the *F* value set between 0.05 and 0.15 (Tabachnick & Fidell, 2001). Cross-validation of the model was performed to assess the accuracy of predicting the same outcome variables for an independent dataset (Field, 2005). The results of the DFA were used to determine which variables best predicted membership to each group. By examining membership for one key comparison of interest (i.e., elite vs. club, or adult vs. youth batters), this approach lessens the chance of spurious findings on the basis of complex interactions with ball-length.

Alpha was set at .05 for all comparisons, with the exception that Bonferroni corrections were used to follow up significant effects found during ANOVA testing. The Greenhouse-Geisser correction was used in any cases where the assumption of sphericity was violated, an important consideration given the slight imbalance in the group sizes. Partial eta squared (η_p^2) and Cohen's *d* values were calculated to indicate the effect size where appropriate.

Results

The mean group results for each of the dependent variables are presented in Table 1. In the text, for the sake of simplicity, generally only the significant main or interaction effects are reported. When reporting significant findings, we report the M ± SD as the mean and standard deviation across participant means. In the following sections, we first report all main and interaction effects of skill (under the heading 'Skill-related differences'), and then report all main and interaction effects of age (under the heading 'Age-related differences').

Skill-related differences.

Batting performance. The elite and club batters were clearly discriminated by their interceptive accuracy on the batting task (see also Weissensteiner, Abernethy, & Farrow, 2011), with the elite batters achieving a significantly higher percentage of good bat-ball contacts than the club batters (elite M = 88.0%, SD = 21.8; club M = 64.0%, SD = 22.1; $F(1, 37) = 24.51$, $p < .001$, $\eta_p^2 = .4$). The superior performance of the elite batters could not be explained by a potential trade-off in the forcefulness of bat-swing between the two groups (% trials with a high FoBS score; elite M = 48.7%, SD = 28.2; club M = 45.0%, SD = 28.6; $F(1, 37) = 0.35$, $p = .56$, $\eta_p^2 = .01$), demonstrating that the elite batters were better able to intercept the target than the club batters were (rather than being more conservative in their approach to interception).

Gaze and head position relative to the ball. The gaze findings provide support for only some of the key conclusions made by previous studies of visual-motor control. On average, the elite batters directed their gaze further ahead of the ball than the club batters (mean gaze-ball angle; elite M = -0.6 deg, SD = 2.0; club M = 0.4 deg, SD = 2.0; $F(1, 37) = 5.15$, $p = .029$, $\eta_p^2 = .12$; Figure 2), consistent with the idea that the elite batters are more anticipatory in their visual-motor behaviour. We return to this point shortly.

Mann, et al. (2013) reported that two world-class batters egocentrically tracked the ball more closely than two lesser-skilled batsmen did, however this finding did not generalise when averaged across the wider population of batters tested in our study (mean head-ball angle; elite M = 3.1 deg, SD = 2.9; club M = 3.7 deg, SD = 3.0; $F(1, 37) = 0.99$, $p = .327$, $\eta_p^2 = .03$; Figure 3). However, the adult elite batters did coordinate their eyes and head in a manner which was unique to that of the other groups of batters. A three-way skill x age x length interaction for gaze-head angle ($F(2, 74) = 3.64$, $p = .031$, $\eta_p^2 = .09$; Figure 4a) revealed that only the adult elite batters maintained a consistent gaze-head angle across trials, irrespective of the ball-length ($p = .89$, $\eta_p^2 = .01$). In contrast, the other groups moved their gaze progressively further ahead of their head direction when the ball bounced further away from them (ps < .012, η_p^2s > .57). This suggests that the adult elite batters account for the different ball-lengths by coordinating the movement of both their eyes *and* head whereas the remaining batters rely more on the independent rotation of either the eyes *or* head.

Predictive saccades. For the blocked-straight trials, a summary of the saccadic behaviour of an exemplar batter from each of the four groups of batters is presented in Figure 5. Land and McLeod (2000) reported that elite batters initiate their saccade towards ball-bounce earlier than less-skilled batters do. This was not the case in the present study, with no difference in the timing of the saccades towards ball-bounce (elite M = 325 ms, SD = 28; club M = 310 ms, SD = 42; $F(1, 18) = 1.96$, $p = .179$, $\eta_p^2 = .10$), or in the frequency of those saccades to ball-bounce (elite M = 47.7%, SD = 38.3; club M = 45.2%, SD = 40.7; $F(1, 39) = 0.09$, $p = .768$, $\eta_p^2 = .01$). An interaction was found between skill and ball-length for the timing of the saccades towards ball-bounce ($F(2, 36) = 3.95$, $p = .028$, $\eta_p^2 = .18$); however, the interaction appeared to be a result of the elite batters initiating their saccade to ball-bounce *later* than the club batters did when facing the more challenging good-length trials (elite M = 343 ms, SD = 54; club M = 298 ms, SD = 78; p = .068; d = 0.66), but not when facing the full-length (elite M = 408 ms, SD = 33; club M = 405 ms, SD = 36; p = .821; d = 0.08) or short-length trials (elite M = 232 ms, SD = 34; club M = 249 ms, SD = 63; p = .355; d = 0.34).

Gaze at bat-ball contact. When examining gaze at the moment of bat-ball contact, Mann, et al. (2013) reported that elite batters were more likely to initiate a saccade towards bat-ball contact, and more likely to ensure that gaze was directed towards the ball at contact. Those findings were supported in our study, with the elite batters initiating more saccades towards bat-ball contact than the club batters (elite M = 24.9%, SD = 19.8; club M = 11.3%, SD = 19.6; $F(1, 39) = 5.06$, $p = .03$, $\eta_p^2 = .12$), and with the elite batters more likely to direct gaze towards the ball at the moment of bat-ball contact (elite M = 46.1% of trials, SD = 26.0; club M = 26.1%, SD = 25.9; $F(1, 34) = 5.61$, $p = .024$, $\eta_p^2 = .14$). When compared across all ball-lengths, the gaze of the club batters was more likely to lag behind the ball at the moment of bat-ball contact than the elite batters (% $BBC_{lagging}$; elite M = 28.6%, SD = 40.8; club M = 50.0%, SD = 39.8; $F(1, 34) = 5.73$, $p = .022$, $\eta_p^2 = .14$). These differences were however superseded by interactions with ball-length, with a skill x ball-length interaction for percentage of saccades towards bat-ball contact ($F(2, 78) = 7.51$, $p = .001$, $\eta_p^2 = .16$; Figure 4b) and for % $BBC_{contact}$ ($F(2, 68) = 3.565$, $p = .034$, $\eta_p^2 = .1$; Figure 4c). The skill advantage was particularly evident against the short-length trials: elite batters initiated more saccades to bat-ball contact than the club batters did when facing the short-length trials ($p = .003$; $d = 1.0$), but not when facing the good-length (p = .552; d = 0.18) or full-length trials (p = .357; d = 0.29). Similarly, the elite batters directed their gaze towards the ball at contact more frequently than the club batters did when facing the short-length trials (p = .009; d = 0.88), but not when facing the good-length (p = .238; d = 0.37) or full-length trials (p = .309; d = 0.32). This is generally consistent with the findings of Mann et al. (2013), who found that a second predictive saccade was most likely to be produced against short-length trials (and gaze more likely to be aligned with bat-ball contact), because the ball bounces further away from the batter, who therefore has more time available in which to produce a post-bounce saccade.

Discriminant function for skill. A stepwise discriminant function analysis was performed, following a MANOVA, to determine which variable(s) most strongly discriminated between skill levels and how accurately group membership could be predicted. When collapsed across all ball-lengths, a significant discriminant function equation was derived for the prediction of skill (D = -1.5 + 0.04 * [% $BBC_{lagging}$]; F = 5.57; df (1, 38); p = .024; group centroids: elite = -0.36, club = 0.39). The sole predictor in the model was the ability to align gaze with the ball at the moment of bat-ball contact (see Mann, et al., 2013). The model accurately predicted 71.4% of cases, with 86.4% of elite and 55.0% of club batters categorised correctly. Cross validation revealed that the successful classification of skill levels did not change.

Age-related differences. Batting performance was not influenced by the age of the batters, with no difference between the adult and youth batters in either the percentage of good bat-ball contacts (adult M = 77.6%, SD = 21.1; youth M = 74.4%, SD = 22.7; $F(1, 37) = 0.42$, p = .519, η_p^2 = .01) or the percentage of trials with high FoBS (adult M = 41.6%, SD = 27.4; youth M = 50.1%, SD = 29.4; $F(1, 37) = 2.80$, p = .103, η_p^2 = .07). There were almost no differences in visual-motor behaviour between the adult and youth batters, and no interactions, suggesting that any skill-related differences in adulthood are present by late adolescence. The one exception was that with age, the batter's ability to direct their gaze towards the ball at bat-ball contact did appear to change for certain ball-lengths (age x ball-length interaction for % $BBC_{contact}$; $F(2, 68)$ = 4.24, p = .018, η_p^2 = .11). Although the follow-up tests failed to reach significance, the interaction appeared to be a result of the adult batters tending to decrease the proportion of trials where gaze was directed towards the ball at contact when facing short-length trials (p = .141, d = 0.48), but not for good-length (p = .555, d = 0.18) or full-length trials (p = .824, d = 0.07). Given the unexpected nature of the outcome, and that it was not hypothesised, this could represent a chance finding that would require replication before being taken too seriously.

Discriminant function for age. The MANOVA analysis failed to find any variables that significantly differed across the two age groups, and so there were no variables to enter into the DFA.

Discussion

The overall findings from this section provide support for only some of those widely cited findings about skill-based differences in visual-motor behaviour when intercepting a fast-moving target. This highlights the limitations of previous studies that have adopted case-study designs, as they may be too sensitive to individual differences in visual-motor control and therefore may not accurately represent the visual-motor behaviour that exists across the wider population.

In this study, we were not able to replicate the widely cited finding that skilled batters make faster predictions by initiating earlier saccades towards ball-bounce than club batters do (see Land & McLeod, 2000). In fact, while there were no differences across skill for the full and short-length deliveries, the elite batters tended to initiate their saccades *later* than the club batters did when facing the good-length deliveries (which are generally considered to be the most difficult to intercept). Instead, this is consistent with the idea that the elite batters, when faced with the more challenging ball-length, may have waited for updated ball-flight information to more accurately predict the future location of the ball (Bootsma & van Wieringen, 1990; Oudejans, Michaels, & Bakker, 1997). Given, though, that this particular finding was unexpected and wrapped up in an interaction between skill and ball-length, replication would be warranted before reaching a firm conclusion that skilled batters in some circumstances initiate *later* saccades.

Our inability to replicate Land and McLeod’s (2000) general finding that skilled batters make earlier saccades cannot be explained by differences between the studies in the skill level of the batters. The most skilled batter in Land and McLeod’s study was of state/provincial level (equivalent to our adult elite group), and the lesser skilled batters were amateur/club level batters (equivalent to our adult club group). Rather, the results are probably best explained by either the simplified task design employed by Land and McLeod (i.e., facing a slower ball-speed with predictable ball trajectories), and/or by the sensitivity of their case-study design to individual differences between participants (see Sarpeshkar & Mann, 2011). In sum, our findings challenge the notion that skilled batters perform earlier predictive saccades when intercepting fast-moving targets (also see Mann, et al., 2013).

The ability of batters to initiate a second anticipatory saccade towards bat-ball contact (and to maintain gaze there when hitting the ball) has previously been shown to distinguish skilled from lesser-skilled performers (see Mann, et al., 2013). The results from this study support the validity of these measures as key markers of batting expertise. The elite batters performed more anticipatory saccades to bat-ball contact, and were more likely to co-locate gaze with the ball at the moment of bat-ball contact. This supports the idea that skilled batters do whatever is necessary to direct their gaze towards the predicted location of bat-ball contact (Mann, et al., 2013). By directing their gaze ahead of the ball prior to bat-ball contact, skilled batters may be able to compare the predicted and actual ball-flight information to facilitate a more accurate estimation of the moment of bat-ball contact when compared to what is possible when simply tracking the ball (see Ripoll & Fleurance, 1988). This in turn may also promote successful interception through the continuous regulation of bat-swing as late as is permissible (see Bootsma & van Wieringen, 1990). With the gaze of the club batters generally lagging behind the ball at the moment of bat-ball contact, it appears that the skilled batters have a better capacity to '*watch the ball onto the bat*' (accurately discriminating the skilled from lesser-skilled batters in 71.4% of cases; see Mann, et al., 2013).

Another key marker of batting expertise proposed by Mann, et al. (2013) was that skilled batters were able to rotate their head in a fashion that allowed them to continuously align their head with the ball (reducing the position of the ball to a single egocentric direction). The results from this study however *do not* support the generalisation of this funding across the wider population, with no difference in the head-ball angle found across the elite and club-level batters. This might be a result of a difference in the skill level of the batters between the two studies. The two elite batters in the Mann et al. study were two of the world's best international-level batters, whereas there was much more variability in the skill level of the elite batters tested in our study (ranging from state to international-level batters). It may be that the low head-ball angle reported for the exceptional batters in the Mann et al. study is a behaviour seen in only the very best batters. This is not to say though that the batter's head direction does not play an important role in the tracking strategies of the batters. In fact, the results from this study suggest that the adult elite batters were better able to coordinate the movements of their eyes *and* head when tracking the ball to maintain a similar gaze-head angle across all ball-lengths. Previous studies suggest that this synergistic movement of the eyes and head may reflect the performer's ability to predict how the target's flight-path is likely to unfold (e.g., Brown, 1990). This is consistent with the idea that with an accumulation of experience facing the different ball-flight trajectories, performers can better orchestrate the coordination of their head and eyes, allowing them to be better able to predict the future location of the target (also see Aivar, Hayhoe, Chizk, & Mruczek, 2005; Collins & Barnes, 1999). In other words, the development of learned internal models of ball-flight characteristics may allow performers to adopt a flexible, yet specific coordination of their eye and head movementd to prepare for the different ball-lengths (Diaz, Cooper, & Hayhoe, 2013; Hayhoe, McKinney, Chajka, & Pelz, 2012). As a result, when tracking the ball, the ability to maintain a similar gaze-head angle across all ball-lengths may provide batters with a consistent reference frame from which to better predict where the ball is likely to bounce, and also to more accurately guide them towards the location at which it will arrive (e.g., Oudejans, et al., 1999; Zaal & Michaels, 2003). In contrast, the other batters who tended to independently rotate the eyes and head may be less certain of the future location of the ball when it bounces on different ball-lengths.

There were very few differences between the visual-motor behaviour of the adult and youth batters in this study. If there were to be age-related differences in the batter's gaze behaviour, then this would suggest that a greater accumulation of experience and/or maturation was necessary during adulthood for the development of expert-like gaze behaviour. However, the results show that almost all skill-based differences present in adulthood have been acquired by late adolescence. Interestingly, there was not even a difference in the interceptive performance of the adult and youth batters (M = 77.6 vs 74.4% respectively; p = .519). This suggests that either there was no difference in the proficiency for batting between the two groups, or that the simplified measures of batting performance used here (and elsewhere) may be incapable of discriminating the more refined skills likely to be necessary for an elite youth batter to develop into an elite batter at the *senior* level of competition. While batters may have successfully hit the ball, little is known about whether they were successful in scoring runs, or decreasing the likelihood of dismissal, yet both of these factors are critical when examining performance during cricket batting (see Mann, et al., 2010). In particular, adult batters are more likely to have developed higher-level cognitive strategies necessary for batting that are not measurable using the current experimental design (Sutton, 2007; Weissensteiner, et al., 2008).

Section II: Does the *Possibility* of Ball-Swing Influence Batting Performance and Visual-Motor Behaviour When Hitting Straight Balls?

Existing studies of visual-motor behaviour have largely employed simplified designs that fail to account for the natural variation in ball-flight trajectories that can occur in the natural environment. Instead, designs are often used that may help to facilitate prediction (e.g., no variation in ball-flight, or the use of ball-machines which may illustrate where the ball will be projected), and this is a problem because these studies often conclude that experts have a superiority in their ability to predict the future location of the ball. The aim of Section II was to compare performance on the blocked-straight and random-straight trials to determine whether the *possibility* of variation (in this case, ball-swing) would alter visual-motor behaviour, even when the ball does not swing. If the possibility of ball-swing significantly influences the ability to predict the future location of a target, then differences in visual-motor behaviour would be expected even when facing trials that follow a straight trajectory. This should result in less predictive gaze behaviour, with gaze being less likely to be in advance of the ball. If the possibility of ball-swing does alter visual-motor behaviour, then it was expected that the elite batters would be better able to account for this uncertainty and therefore there would be less change in their visual-motor behaviour than there would be for the lesser-skilled batters (Gray, 2002).

Analysis

To examine the influence of a batter's uncertainty about the ball-flight on visual-motor behaviour, the analysis for this section compared behaviour when hitting the blocked-straight and the random-straight trials (that is, when the straight trials were not mixed, and were mixed, with swinging trials respectively). A total of 891 out of a possible 1204 blocked-straight and random-straight trials (74%) were examined, including 287 trials for the adult elite group, 190 for the adult club group, 209 for the youth elite group, and

205 for the youth club group. A total of 251 trials were excluded because the batter did not swing their bat (21% of trials), and 62 trials because of technical difficulties with the Mobile eye (5% of remaining trials).

Dependent variables were analysed using (i) a 2 (Skill: elite, club) x 2 (Age: adult, youth) x 2 (Uncertainty: blocked-straight, random-straight) x 2 (Length: full, good) ANOVA with repeated measures on the last two factors, and (ii) a DFA to predict group membership for the random-straight vs blocked-straight conditions.

Results

The mean results comparing each of the dependent variables when facing the blocked-straight and random-straight trials are presented in Table 2. In this section, we focus on the main and interaction effects of uncertainty to determine whether the *possibility* of ball-swing influenced the batter's behaviour.

Batting performance. Strikingly, the simple awareness that the ball *could* swing resulted in a significant decrease in the percentage of good bat-ball contacts across all batters (blocked-straight M = 76.1%, SD = 13.8; random-straight M = 70.3%, SD = 16.1; $F(1, 38) = 4.67$, $p = .037$, $\eta_p^2 = .11$). Again, this result could not be explained by a change in the forcefulness of bat-swing across the two conditions (blocked-straight M = 47.1%, SD = 19.3; random-straight M = 41.0%, SD = 21.0; $F(1, 38) = 2.01$, $p = .16$, $\eta_p^2 = .05$). Surprisingly though, the main effect for the percentage of good bat-ball contacts was over-ridden by a significant skill x uncertainty interaction, with the batting performance of the elite batters *more* (rather than less) influenced by the possibility of ball-swing than was the performance of the club batters (skill x uncertainty interaction for percentage of good bat-ball contacts, $F(1, 38) = 10.01$, $p = .003$, $\eta_p^2 = .21$; Figure 6a). The co-presentation of straight and swinging trials reduced the batting performance of the elite batters (blocked-straight M = 86.3%, SD = 9.5; random-straight M = 72.1%, SD = 13.6; $p < .001$; $d = 1.21$), but not that for the club batters (blocked-straight M = 66.0%, SD = 17.1; random-straight M = 68.7%, SD = 18.1; $p = .54$; $d = 0.15$). In fact, the performance of the elite batters was indistinguishable from that of the club batters in the random-straight trials ($p = .48$; $d = 0.22$).

Gaze and head position relative to the ball. There were significant changes in gaze when the batters were aware that the ball could swing. Gaze was less predictive, in that it was directed further behind the ball in the random-straight trials than it was in the blocked-straight trials (mean gaze-ball angle; blocked-straight *M* = 0.2 deg, *SD* = 1.6; random-straight *M* = 0.7 deg, *SD* = 1.5; $F(1, 38) = 5.91$, $p = .02$, $\eta_p^2 = .14$). There was though in the random-straight trials an increase in the *consistency* of the position of gaze relative to the ball (SD for gaze-ball angle; blocked-straight *M* = 3.8 deg, *SD* = 1.9; random-straight *M* = 3.2 deg, *SD* = 1.8; $F(1, 38) = 5.03$, $p = .031$, $\eta_p^2 = .12$). Moreover, batters when facing the random-straight trials were more consistent in their ability to co-align their gaze and head with the ball in the *lateral* direction (*SD for lateral gaze-ball angle*, blocked-straight *M* = 1.6 deg, *SD* = 1.3; random-straight *M* = 1.2 deg, *SD* = 0.9; $F(1, 38) = 4.35$, $p = .044$, $\eta_p^2 = .1$; *SD for lateral gaze-head angle*, blocked-straight *M* = 2.2 deg, *SD* = 1.7; random-straight *M* = 1.8 deg, *SD* = 11.6; $F(1, 38) = 11.0$, $p = .002$, $\eta_p^2 = .23$; *SD for lateral head-ball angle*, blocked-straight *M* = 1.6 deg, *SD* = 1.2; random-straight *M* = 1.3 deg, *SD* = 0.8; $F(1, 38) = 4.57$, $p = .039$, $\eta_p^2 = .11$).

The batter's ability to align the direction of their head with the ball has been proposed as a marker of expertise (Mann, et al., 2013), though this is in question on the basis of the results of Section I. Here, head tracking was poorer when the ball could swing (i.e., against the random-straight trials) when batters faced the full-length (but not good-length) deliveries (i.e., uncertainty x length interactions for head-ball angle, $F(1, 38) = 10.37$, $p = .003$, $\eta_p^2 = .21$, Figure 6b; and lateral head-ball angle, $F(1, 38) = 5.27$, $p = .027$, $\eta_p^2 = .12$; Figure 6c). When compared to the blocked-straight trials, the batters directed their head further behind the ball in the random-straight trials when the ball bounced on a full-length ($p = .05$; $d = 0.22$), but not on a good-length ($p = .144$; $d = 0.18$). Head tracking of the ball is typically better when facing full-length trials than it is against good-length trials (Mann, et al., 2013), but the effects of uncertainty decreased the batter's head tracking against the full-length deliveries to a level that was no longer distinguishable from the good-length deliveries.

Predictive saccades. The effect of uncertainty also influenced the anticipatory saccades of the batters (see Figure **5**B). In the random-straight trials when there was more uncertainty about ball-flight, batters delayed the timing of their saccade towards ball-bounce (blocked-straight *M* = 358 ms, *SD* = 33; random-straight *M* = 389 ms, *SD* = 28; $F(1, 18) = 24.3$, $p < .001$, $\eta_p^2 = .58$), and initiated fewer saccades both towards ball-bounce (blocked-straight *M* = 48.8% of trials, *SD* = 29.1; random-straight *M* = 42.0%, *SD* = 28.9;

$F(1, 39) = 5.22$, $p = .028$, $\eta_p^2 = .12$) and towards bat-ball contact (blocked-straight $M = 9.1\%$, $SD = 15.1$; random-straight $M = 3.7\%$, $SD = 8.2$; $F(1, 39) = 6.88$, $p = .012$, $\eta_p^2 = .15$). However, these main effects were overshadowed by significant interactions. First, the delay in initiating a saccade to ball-bounce in the random-straight trials was greater for the club batters (blocked-straight $M = 350$ ms, $SD = 36$; random-straight $M = 395$ ms, $SD = 22$; $p = .002$; $d = 1.52$) than it was for the elite batters (blocked-straight $M = 367$ ms, $SD = 28$; random-straight $M = 384$ ms, $SD = 31$; $p = .035$; $d = 0.56$), though there was a delay for both groups (skill x uncertainty interaction, $F(1, 18) = 5.27$, $p = .034$, $\eta_p^2 = .23$; Figure 6d). The greater delay in the club batters was consistent with our hypothesis. Second, uncertainty in ball-flight was more likely to influence saccades on the good-length as opposed to the full-length trials, with batters against the good-length trials delaying the timing of the saccade to ball-bounce ($p < .001$; $d = 1.2$; Figure 6e) and initiating fewer saccades towards bat-ball contact ($p = .008$; $d = 0.47$; Figure 6f). When facing full-length trials however, uncertainty did not change the batter's timing of the saccade to ball-bounce ($p = .781$; $d = 0.06$) or the percentage of saccades towards bat-ball contact ($p = .915$; $d = 0.02$; though see floor effect in Figure 6f). Although we made no specific hypotheses about the specific effect of uncertainty on different ball-lengths, if true, this finding suggests that the good-length trials, which are already the most challenging ball-length to face, became even more challenging in the presence of uncertainty.

Gaze at bat-ball contact. In the presence of uncertainty, the batters were less likely to co-locate their gaze with the ball at the moment of bat-ball contact (blocked-straight $M = 28.2\%$, $SD = 28.5$; random-straight $M = 16.6\%$, $SD = 19.2$; $F(1, 35) = 15.37$, $p < .001$, $\eta_p^2 = .31$), with gaze more likely to lag behind the ball when it was hit (blocked-straight $M = 46.2\%$ of trials, $SD = 29.1$; random-straight $M = 64.1\%$, $SD = 22.3$; $F(1, 35) = 29.35$, $p < .001$, $\eta_p^2 = .46$). Given that the ability to watch the ball at the moment of bat-ball contact is one of the key predictors of skill in batting (see Section I), it is not surprising that batting performance decreased significantly when facing these trials.

Discriminant function for uncertainty. A stepwise discriminant function analysis accurately discriminated between blocked-straight and random-straight trials ($D = -7.85 + 0.03 * [\%\ BBC_{contact}] + 0.03 * [\%\ BBC_{lagging}] - 0.05 *$ [percentage of trials with saccades towards bat-ball contact] + 16.85 * [timing of saccade to ball-bounce], $F = 8.05$; df 4, 60; $p < .001$; group centroids: blocked-straight = -0.61; random-straight = 0.86). The predictors of the random-straight trials were the delayed initiation of saccades towards ball-bounce, fewer saccades towards bat-ball contact, a reduced likelihood of co-locating gaze with the ball at the moment of bat-ball contact, and an increased likelihood of gaze lagging behind the ball at contact. The model accurately predicted group membership for 72.3% of cases with 73.7% of blocked-straight and 70.4% of random-straight trials categorised correctly. Cross-validation correctly re-categorised 70.8% of cases with 73.7% of blocked-straight and 66.7% of random-straight trials.

Discussion

The uncertainty generated when the batters were aware that the ball *could* swing had a striking effect on both batting performance, and visual-motor behaviour, even though the ball continued to follow a rectilinear (straight) trajectory. There was a significant decrease in the interceptive accuracy of the batters, though surprisingly this was largely attributable to a decrease in the performance of the *elite* batters, who reduced their interceptive quality to a level that was indistinguishable from that of the club batters. On the basis of findings in baseball batting, Gray (2002) had proposed that skilled batters should be *better* able to account for uncertainties in ball-fight. This was not always the case in our study, a surprising finding that is not easy to reconcile. A closer look at the type of trials in which the elite batters had an advantage in the blocked-straight but not random-straight trials suggests that the effect could at least in part be explained by the aggressiveness of the shots played by the elite batters. The interceptive advantage apparent for the elite batters in the blocked-straight trials was based largely on their performance when playing more aggressive shots, and that it was those shots that were more adversely affected by uncertainty. We have recently found that batters delay most of their movements in the presence of uncertainty about ball-flight (presumably to wait and establish whether the ball will swing; Sarpeshkar, et al., 2017), and given the increased temporal precision necessary to successfully execute those more aggressive actions, it may be that the kinematic delays more adversely affect performance in the more aggressive shots that demand higher temporal precision, and for which the elite batters are usually more successful.

It could be questioned whether practice and/or fatigue effects could provide an alternate explanation for the differences in performance found between the two uncertainty conditions, given that there were a different number of trials between the blocked-straight and random-straight conditions. There were 18 trials in total in the block of straight-only trials (with only the 'good' and 'full' length trials included for analysis in this section, n = 12), and there were 48 trials in the block of straight and swinging trials (with only the 'good' and 'full' length straight trials included for analysis in this section, n = 16). To check for practice or fatigue effects as a result of the different trial numbers, we broke the blocks of trials included for analysis in this section for each participant into four bins, with each bin representing a quarter of the trials in that block ('First quarter', 'second quarter', 'third quarter', 'fourth quarter'). Then, we re-ran the ANOVA testing for the percentage of good bat-ball contacts using a 2 (skill: elite, club) x 2 (age: adult, youth) x 2 (uncertainty: blocked-straight, random-straight) x 4 (bin: first quarter, second quarter, third quarter, fourth quarter) ANOVA. If there were any practice or fatigue effects that differed across the two conditions, then we would have expected to find a significant uncertainty x bin interaction. However, this wasn't the case (p = .79), providing reassurance that practice or fatigue effects cannot explain the differences in batting performance.

The changes in batting performance found as a result of uncertainty were also accompanied by significant changes in gaze. In general, the uncertainty generated by the possibility of ball-swing resulted in changes in gaze that generally would have been considered to be 'more novice-like'; that is, gaze lagged further behind the ball, less predictive saccades were performed to both ball-bounce and bat-ball contact (and those saccades to ball-bounce that were performed were delayed), and ultimately batters were less likely to align their gaze with the ball at contact. The changes in saccadic behaviour were largely attributable to changes apparent when facing the good-length trials, evidently making it even more difficult to intercept what is already the most challenging ball-length (Bradman, 1958; Woolmer, Noakes, & Moffett, 2008). When the ball bounces at a good-length, it seems that the additional uncertainty surrounding the possibility of ball-swing amplifies the existing uncertainty that batters generally experience about the direction in which they should move (Pinder, Davids, & Renshaw, 2012), resulting in delayed movements (Sarpeshkar, et al., 2017), and changes in visual-motor behaviour. There were increases in the *consistency* of the location of gaze and the head relative to the position of the ball when facing the random-straight trials, though this most likely reflects the decrease in anticipatory behaviour (e.g., less saccades) observed in that condition.

Although it is tempting to conclude that the increased uncertainty in the random-straight condition resulted in more 'novice-like' gaze behaviour that was less predictive, the findings do question the basis on which we have developed our understanding of what constitutes 'expert-like' gaze behaviour. More predictive behaviour is generally considered to be characteristic of expert performance (e.g., earlier predictive saccades, more saccades, aligning gaze with the ball at contact), yet these findings have been demonstrated largely using experimental designs that may encourage prediction. Most studies have employed ball-projection machines that either present trials in a blocked fashion where the bounce point does not vary (e.g., Croft, et al., 2010), or where the angle of the ball machine may help to predict the bounce point (e.g., Land & McLeod, 2000). As a result, it is possible that these studies have accentuated the predictive nature of gaze, because they presented scenarios in which experts were better able to assimilate their knowledge of previous trials to facilitate performance (and predictive gaze) in subsequent trials (e.g., Gray, 2002). The competitive environment though is likely to be less predictable than what is experienced in most experiments, and so it may be that the expert advantage in the performance environment results in less prediction than what has been captured in experimental conditions.

Irrespective of the interpretation of the present findings, they do highlight the surprising impact of uncertainty and therefore 'top-down' cognitive influences on interceptive performance as a result of contextual information available to the performer (Sutton, 2007). There is a growing understanding of how contextual information can alter performance when anticipating the actions of others (Abernethy, Farrow, Gorman, & Mann, 2012; Abernethy, Gill, Parks, & Packer, 2001; Cañal-Bruland & Mann, 2015; Mann, Schaefers, & Cañal-Bruland, 2014), and our study shows that this influence extends to significant changes in visual-motor behaviour, with top-down influences shaping how dynamic time-constrained interceptive tasks such as cricket batting are performed. This raises an additional dimension for future studies to consider when designing an ecologically valid environment for the examination of interceptive skill.

Section III: Does the *Presence* of Ball-Swing Significantly Alter Interceptive Performance and Visual-Motor Behaviour?

Curving ball-flight trajectories significantly reduce interceptive performance, possibly because the visual system is unable to exploit the informational variables it would typically rely on when intercepting rectilinear trajectories (Craig, et al., 2011). The aim of Section III was to examine whether there are changes in visual-motor behaviour when intercepting a curving rather than rectilinear trajectory. If curving trajectories do impair a batter's visual-motor behaviour then we expected to find more 'novice-like' gaze behaviour that is less predictive when the ball did swing (i.e., fewer predictive saccades, saccades initiated later, and gaze less likely to be in advance of the ball). If oblique saccades assist in the interception of curving trajectories, then we expected to find an increase in the number of oblique saccades in the 'swinging' trials. Moreover, we expected that the requirement to intercept a curving trajectory would have a greater influence on the visual-motor behaviour of the club batters than it would on the elite batters.

Analysis

To determine whether batters adapted their visual-motor behaviour when hitting a ball that *did* or *did not* swing, the analysis for this section compared the swinging trials with those that did not swing (using the random-straight trials to exclude the *possibility* of ball-swing as a reason for any changes in behaviour). A total of 1326 out of 2064 random-straight and swinging trials were examined (64% of trials): 431 trials for the adult elite batters, 287 for the adult club, 321 for the youth elite, and 287 for the youth club. A total of 619 trials were excluded because the batters did not play a shot (30% of trials), and 119 trials because of technical difficulties with the Mobile Eye (6% of remaining trials).

Dependent variables were analysed using (i) a 2 (Skill) x 2 (Age) x 2 (Type of delivery: straight, swing) x 2 (Length) ANOVA with repeated measures on the last two factors, and (ii) a DFA to predict group membership for the straight and swinging trials.

Results

The mean results comparing each of the dependent variables when facing straight and swinging trials are presented in Table 3. In this section, the main and interaction effects of the type of delivery (straight vs. swing) are reported to determine whether the *presence* of ball-swing influences visual-motor behaviour.

Batting performance. There was a striking decrease in batting performance when batters attempted to hit balls that swung. When compared to hitting straight balls, against the swinging trials there was a significant decrease in the percentage of good bat-ball contacts (random-straight M = 70.3%, SD = 16.1; swinging M = 50.5%, SD = 17.4; $F(1, 38) = 45.1$, $p < .001$, $\eta_p^2 = .54$; see also Craig, et al., 2011; Craig, et al., 2006). The decrease in the quality of contact in the swinging trials could not be explained by a difference in the aggressiveness of the shots played between the two conditions (random-straight M = 41.0%, SD = 21.0; swinging M = 37.8%, SD = 20.9; $F(1, 38) = 1.18$, $p = .285$, $\eta_p^2 = .03$), demonstrating that interception is more difficult to achieve in the presence of ball-swing. The lack of any higher-order interactions shows that batting performance decreased irrespective of the skill level, age, or ball-length faced.

Gaze and head position relative to the ball. The relative positions of gaze, the head, and the ball are illustrated for the random-straight and swinging trials in Figure 7. Ball-swing resulted in skill-based differences in eye and head movements that were not apparent when facing the straight balls. For instance, a skill x type-of-delivery interaction for gaze-ball angle ($F(1, 37) = 6.04$, $p = .019$, $\eta_p^2 = .14$; Figure 8a) showed that the elite batters were better able to direct their gaze towards the ball when facing the swinging trials than the club batters were ($p = .022$, $d = 0.78$), but not when facing the random-straight trials ($p = .17$, $d = 0.43$). Generally, there was no difference in the magnitude and consistency of the head-ball angle between the straight and swinging trials (Figure 7), except when the elite batters faced the full-length deliveries, in which case they improved their head-ball angle (i.e., skill x delivery x length interactions for head-ball angle, $F(1, 36) = 6.48$, $p = .015$, $\eta_p^2 = .15$; elite full-length [$p = .001$, $d = 0.43$], elite good-length [$p = .053$, $d = 0.26$], club full-length [$p = .399$, $d = 0.08$], club good-length [$p = .31$, $d = 0.13$]; and SD for head-ball angle, $F(1, 36) = 4.85$, $p = .034$, $\eta_p^2 = .12$; elite full-length [$p = .006$, $d = 0.56$], elite good-length [$p = .043$, $d = 0.31$], club full-length [$p = .704$, $d = 0.05$], club good-length [$p = .14$, $d = 0.27$]). Collectively, these results provide support for the idea that the magnitude of some skill-based differences in gaze *increase* when required to hit a ball that follows a curving trajectory.

In addition to the differences found across skill, there were other effects that were present for all batters. The swinging trajectories reduced the likelihood that the batters directed their gaze ahead of their head, compared to when facing the straight trials (mean gaze-head angle; random-straight *M* = -2.7 deg, *SD* = 2.2; swinging *M* = -2.4 deg, *SD* = 2.0; $F(1, 36) = 6.2$, $p = .018$, $\eta_p^2 = .15$). However, this was largely because the batters maintained closer *and* more consistent head-ball coupling when facing the swinging balls (mean head-ball angle, random-straight *M* = 3.6 deg, *SD* = 2.4; swinging *M* = 3.2 deg, *SD* = 2.2, $F(1, 36) = 6.27$, $p = .017$, $\eta_p^2 = .15$; SD for head-ball angle, random-straight *M* = 5.1 deg, *SD* = 2.8; swinging *M* = 4.3 deg, *SD* = 2.3, $F(1, 36) = 9.32$, $p = .004$, $\eta_p^2 = .21$; Figure 7). The lateral head-ball angle was more variable when facing the swinging trajectories (SD for lateral head-ball angle; random-straight *M* = 1.4 deg, *SD* = 0.8; swinging *M* = 1.7 deg, *SD* = 0.8; $F(1, 36) = 12.87$, $p = .001$, $\eta_p^2 = .26$), though this was probably because the analysis of the swinging trials combined both in-swinging and out-swinging deliveries.

Predictive saccades. Contrary to expectations, ball-swing did not necessarily reduce the likelihood that batters would perform a predictive saccade. There was no change in the frequency of saccades to ball-bounce when facing the swinging trajectories (random-straight M = 42.0%, SD = 28.9; swinging M = 41.0%, SD = 29.6; $F(1, 39) = 0.16$, $p = .69$, $\eta_p^2 = .00$), though there was a change in the proportion of trials where saccades were made towards bat-ball contact. Saccades to bat-ball contact are typically produced on only some good-length trials (≈20%), and rarely ever against full-length trials (see Section I). Therefore it is unlikely that we would expect changes against the full-length trials. Consistent with this, a three-way skill x delivery x length interaction ($F(1, 39) = 5.12$, $p = .029$, $\eta_p^2 = .12$; skill x delivery interaction, $F(1, 39) = 4.98$, $p = .031$, $\eta_p^2 = .11$) revealed skill-related differences for the good-length trials: ball-swing tended to reduce the likelihood of saccades towards bat-ball contact for the elite batters (random-straight *M* = 13.6%, *SD* = 20.5; swinging *M* = 6.2%, *SD* = 10.0; *p* = .065, *d* = 0.36), yet surprisingly club batters tended to only produce the saccade when the ball swung (random-straight *M* = 0.0%, *SD* = 0.0; random-swing *M* = 2.9%, *SD* = 6.6; *p* = .064, *d* = 0.62).

The analysis of the *oblique* saccades shows that the elite batters were more likely to modify their saccadic behaviour to adapt to the curving trajectories. In general, batters performed more oblique saccades towards ball-bounce when hitting the swinging trajectories (random-straight *M* = 4.3%, *SD* = 9.0;

swinging M = 7.5%, SD = 9.0; $F(1, 39) = 9.51$, $p = .004$, $\eta_p^2 = .2$). However, a skill x type-of-delivery interaction ($F(1, 39) = 4.34$, $p = .044$, $\eta_p^2 = .1$; Figure 8b) shows that the elite batters adapted their behaviour so that they performed more oblique saccades when the ball *did* swing, and less when the ball *did not* (random-straight M = 2.7%, SD = 7.2; swinging M = 8.1%, SD = 7.5; $p = .001$, $d = 0.73$), whereas the club batters performed a similar number irrespective of whether the ball did or did not swing (random-straight M = 5.8%, SD = 10.2; swinging M = 6.8%, SD = 10.3; $p = .515$, $d = 0.1$). This shows that the elite batters were better able to discriminate the swinging from straight trials, and to functionally adopt their visual-motor behaviour accordingly.

Gaze at bat-ball contact. In general, ball-swing did not significantly alter the batter's ability to align their gaze with the ball at the moment of bat-ball contact (random-straight M = 16.3%, SD = 19.1; random-swing M = 13.8%, SD = 16.0; $F(1, 36) = 1.54$, $p = .223$, $\eta_p^2 = .04$). This was, however, superseded by a higher-order interaction, with ball-swing influencing the youth batters more than it did the adult batters. A significant three-way age x delivery x length interaction for % $BBC_{contact}$ ($F(1, 36) = 4.76$, $p = .036$, $\eta_p^2 = .12$; and for % $BBC_{lagging,}$ $F(1, 36) = 9.91$, $p = .003$, $\eta_p^2 = .22$) suggests that ball-swing increased the likelihood that the gaze of the youth batters was positioned behind the ball at the moment of bat-ball contact for the full-length trials (random-straight M = 49.1%, SD = 27.4; random-swing M = 66.6%, SD = 20.4; $p = .021$, $d = 0.72$) but not for the good-length trials (random-straight M = 78.2%, SD = 27.0; random-swing M = 71.2%, SD = 19.4; $p = .339$, $d = 0.3$). No differences were found for the adult batters (ps > .499, ds < 0.13).

Discriminant function for swinging trials. A stepwise discriminant function analysis accurately discriminated between random-straight and swinging trials (D = 0.36 * [gaze-ball angle] + 0.05 * [percentage of saccades to bat-ball contact] + 0.05 * [percentage of oblique saccade towards ball-bounce]; $F = 41.61$; df 3, 82; $p < .001$; group centroids: random-straight = -1.22; random-swing = 1.22). The predictors in the model highlight that against the swinging ball, batters were more likely to direct their gaze closer to the ball, initiate fewer saccades towards bat-ball contact, but increase the prevalence of oblique saccades towards ball-bounce. The model accurately predicted group membership for 90.7% of cases with 100.0% of random-straight and 81.4% of random-swing trials categorised correctly. Cross-validation correctly re-categorised 88.4% of cases with 97.7% of random-straight and 79.1% of random-swing trials.

Discussion

Batting performance was worse when intercepting targets which followed a curving rather than straight trajectory. This supports the findings of previous studies which show that performance decreases against curvilinear trajectories in a virtual environment (Craig, et al., 2011; Craig, et al., 2006).

The decrease in batting performance when intercepting curving trajectories was underpinned by significant changes in visual-motor behaviour. The discriminant function analysis revealed that the best discriminators of gaze on swinging trials were (i) closer alignment between gaze and the ball, (ii) an increase in the proportion of oblique saccades to ball-bounce, (iii) and a decrease in the percentage of saccades to bat-ball contact. The first two discriminators suggest that the batters were able to functionally adapt their gaze to account for the ball-swing. That is, the better gaze-ball alignment suggests that batters attempted to track the ball more closely when the ball was swinging, and the increase in oblique saccades to ball-bounce shows that (the elite) batters were able to account for the lateral deviation of the ball when predicting its' future location. The total number of predictive saccades towards ball-bounce did not change when hitting balls that swung, yet a proportion of those saccades were oblique rather than straight. Critically, these oblique saccades provide evidence of functional adaptions in gaze when intercepting a swinging target in situ, consistent with previous studies conducted in a virtual environment (Smit, et al., 1990). Although oblique saccades are not performed very often (≈7-8% of swinging trials), they provide some evidence to suggest that the human visual system may be more capable of predicting the future location of a swinging ball than previously assumed (Craig, et al., 2006; Port, et al., 1997), offering a new way to better understand how skilled performers make predictions about curvilinear trajectories.

The examination of batting against swinging trajectories revealed new skill-based differences in gaze that were not evident when facing the straight trajectories. The better gaze-ball tracking in the presence of ball-swing was more evident for the elite batters than it was for the club batters, suggesting that elite batters may be better able to foveate the ball to provide a functional means of facilitating interception under the increasing spatio-temporal demands of ball-swing (Brenner & Smeets, 2011; Spering, Schutz, Braun, & Gegenfurtner, 2011). The elite batters also improved their head-ball tracking, and decreased the variability of the tracking in the presence of ball-swing, whereas the club batters did not, again suggesting that the elite batters were better able to adapt their visual-motor behaviour (in this case the head tracking) to assist in the prediction of the future location of the ball (Mann, et al., 2013). Moreover, the predictive saccades of the elite batters to ball-bounce were better attuned to the actual ball-flight characteristics. That is, the elite batters produced oblique saccades when the ball swung, but straight saccades when the ball did not. In contrast, the club batters were just as likely to produce oblique saccades when the ball did or did not swing. This shows that the ability to discriminate between swinging and straight trajectories, and to use that information to better predict the future location of the ball, may be a skill that improves commensurate with the development of expertise in batting. Additionally, the scarcity of any significant interactions with age shows that these skills are likely to emerge by late adolescence and continue into adulthood.

Although the comparison of the random-straight and swinging trials in this section has revealed significant differences in visual-motor behaviour during interception, the magnitude of the changes are relatively similar to those found in the previous section when comparing the blocked-straight and random-straight trials. The requirement to hit targets that follow a swinging trajectory is generally considered to be much more challenging than when hitting targets that simply follow a straight trajectory (Craig, et al., 2011; Dessing & Craig, 2010). However, the introduction of swing in-and-of-itself increases the uncertainty with which the batter can make predictions about ball-flight (unless of course only the same swinging trajectory is used on every trial). In this study, these two key differences have been disentangled to better understand the source of the increased difficulty. The findings suggest that both the ball-swing *and* the uncertainty it creates contribute to the substantial difficulty experienced against curving trajectories.

Section IV: Does the *Direction* of Ball-Swing Significantly Alter Interceptive Performance and Visual-Motor Behaviour?

In a task such as cricket batting, the *direction* of the curvature could significantly impact visual-motor behaviour, because the relative positions of the batter and bowler result in an asymmetry in the flight paths of the ball. The angle of approach of a ball that swings *away* from the batter will initially be more closely aligned with the batter's line-of-sight, and therefore it may be more difficult to detect the nature of the curve to anticipate the future location of the ball (Sarpeshkar, et al., 2017). The aim of Section IV was to establish whether visual-motor behaviour in batting is influenced by the direction of ball-swing. If it is more difficult to detect the ball trajectory of a target that swings *away* from the batter, then we expected to find more novice-like gaze behaviour (that was less predictive) compared to trials where the ball swung *in*.

Analysis

To determine whether there were differences in visual-motor behaviour for the two different directions of curvature, the analysis focused on a comparison of the out-swing and in-swing trials. A total of 844 out of a possible 1376 trials were examined (61% of trials): 273 trials for the adult elite group, 182 for the adult club group, 209 for the youth elite group, and 180 for the youth club group. A total of 446 trials were excluded because the batters did not swing their bat (32% of trials) and 86 trials because of technical difficulties with the Mobile Eye (6% of trials).

Dependent variables were analysed using (i) a 2(Skill) x 2 (Age) x 2 (Direction-of-swing: out-swing, in-swing) x 2 (Length) ANOVA with repeated measures on the final two factors, and (ii) a DFA to predict group membership for the out-swing vs. in-swing trials.

Results

The mean results comparing each of the dependent variables when facing the out-swing and in-swing trials are presented in Table 4.

Batting performance. Interceptive performance was significantly worse when attempting to hit the out-swinging trajectories (percentage of good bat-ball contacts, out-swing M = 42.3%, SD = 26.7; in-swing M = 58.3%, SD = 21.8; $F(1, 38) = 9.25$, $p = .004$, $\eta_p^2 = .2$), even though the batters lowered their forcefulness of bat-swing when the ball swung away (percentage of high FoBS, out-swing M = 29.4%, SD = 26.9; in-swing M = 46.3%, SD = 24.3; $F(1, 38) = 13.01$, $p = .001$, $\eta_p^2 = .26$). The lack of any higher-order interactions shows that this difficulty in hitting out-swinging deliveries held irrespective of the skill and age of the batters, and across both ball-lengths.

Gaze and head position relative to the ball. Consistent with the decrease in performance, batters spent less time with their gaze ahead of the ball when hitting the out-swinging trajectories (% $Gaze_{ahead}$, out-swing *M* = 45.5%, *SD* = 24.9; in-swing *M* = 51.6%, *SD* = 23.0; $F(1, 37) = 6.47$, $p = .015$, $\eta_p^2 = .15$ Figure 9. Instead, gaze lagged further behind the ball (gaze-ball angle, out-swing *M* = 1.0 deg, *SD* = 1.7; in-swing *M* = 0.4 deg, *SD* = 1.7; $F(1, 38) = 8.7$, $p = .005$, $\eta_p^2 = .19$). The direction of ball-swing did not alter the head-ball angle of batters when facing good-length trials ($p = .976$, $d = 0.00$), but the angle did increase when full-length balls swung away from the batter ($p = .008$, $d = 0.19$; direction-of-swing x ball-length interaction for head-ball angle, $F(1, 37) = 4.63$, $p = .038$, $\eta_p^2 = .11$).

Despite the difficulty that the batters experienced when hitting the out-swinging trajectories, their *lateral* head-ball coupling was better when facing those deliveries than it was when facing the in-swinging deliveries. The lateral head-ball angle was lower, and was more consistent, when facing the out-swinging deliveries (mean lateral head-ball angle, out-swing *M* = 0.1 deg, *SD* = 1.2; in-swing *M* = 0.7 deg, *SD* = 1.5; $F(1, 37) = 18.46$, $p < .001$, $\eta_p^2 = .33$; SD for lateral head-ball angle, out-swing *M* = 1.3 deg, *SD* = 0.8; in-swing *M* = 2.2 deg, *SD* = 1.2, $F(1, 37) = 17.49$, $p < .001$, $\eta_p^2 = .32$). However, a significant direction-of-swing x ball-length interaction for the lateral head-ball angle ($F(1, 37) = 11.8$, $p = .001$, $\eta_p^2 = .24$) suggests that the magnitude of this effect might have been larger for the full-length trials (out-swing *M* = 0.8 deg, *SD* = 1.4; in-swing *M* = 1.0 deg, *SD* = 1.4; $p < .001$, $d = .65$) than it was for the good-length ones (out-swing *M* = 0.2 deg, *SD* = 1.2; in-swing *M* = 0.5 deg, *SD* = 1.6; $p = .138$, $d = .2$). Relatedly, the lateral gaze-head angle was also more consistent against the out-swinging trials (out-swing *M* = 1.7 deg, *SD* = 1.0; in-swing *M* = 2.0 deg, *SD* = 1.2, $F(1, 37) = 4.29$, $p = .045$, $\eta_p^2 = .1$). These results are probably best explained by the idea that the out-swinging balls generally follow a more head-on trajectory for a longer duration of ball-flight compared to the in-swinging balls (Diaz, et al., 2009), meaning that less lateral head movements are necessary to couple the direction of the head to the ball. We return to this point shortly.

An interaction between the direction of ball-swing and ball-length for the lateral gaze-ball angle ($F(1, 37) = 13.52$, $p = .001$, $\eta_p^2 = .27$) revealed that the direction of ball-swing did not alter the batter's lateral gaze-ball angle when facing full-length trials ($p = .296$, $d = 0.14$), but batters did direct their gaze closer in line with the out-swinging ball when facing good-length trials ($p = .005$, $d = 0.38$). This was superseded by a somewhat inconsequential three-way age x direction-of-swing x length interaction (F(1, 37) = 6.65, p = .014, η_p^2 = .15) whereby the interaction was found to be a reflection of the adult (but not youth) batters directing their gaze more towards the outside line of the in-swinging ball when facing full-length (p = .187, d = .41) but not good-length deliveries (p = .839, d = .06). No differences were found when facing the more head-on trajectory of the out-swinging balls (ps > .348, ds < .3).

Predictive saccades. The direction of ball-swing did not change the frequency of the saccades to ball-bounce (out-swing M = 38.1% of trials, SD = 31.3; in-swing M = 43.9%, SD = 34.0; F(1, 39) = 1.92, p = .17, η_p^2 = .05); however batters did initiate their saccades *earlier* against the out-swinging trials (out-swing M = 387 ms, SD = 30; in-swing M = 404 ms, SD = 21; F(1, 14) = 6.42, p = .024, η_p^2 = .32; Figure 9). An age x direction-of-swing interaction for the % of oblique saccades to ball-bounce (F(1, 39) = 4.95, p = .032, η_p^2 = .11) suggests that the adult batters tended to initiate *more* oblique saccades than the youth batters did when the ball swung in (p = .143, d = 0.46), but fewer when the ball swung away (p = .25, d = 0.35). Given the unexpected nature of this finding, further verification would be required before taking it too seriously.

Gaze at bat-ball contact. The direction of ball-swing did not significantly alter the likelihood of batters aligning their gaze with the ball at the moment of bat-ball contact (out-swing M = 12.6%, SD = 19.8; in-swing M = 14.8%, SD = 18.1; F(1, 38) = 0.47, p = .50, η_p^2 = .01), though there was a tendency for gaze to lag behind the ball more so when facing in-swinging deliveries (% $BBC_{lagging}$, out-swing M = 62.6%, SD = 26.4; in-swing M = 72.9%, SD = 21.8; F(1, 38) = 4.08, p = .051, η_p^2 = .1). Also, when the ball swung in, batters were more likely to direct their gaze in the post-contact direction of the ball before bat-ball contact (% $BBC_{post\text{-}contact}$, F(1, 38) = 4.97, p = .032, η_p^2 = .12; out-swing M = 14.5%, SD = 16.2; in-swing M = 22.6%, SD = 24.8).

Discriminant function for the direction of ball-swing. A stepwise discriminant function analysis accurately discriminated between outswing and inswing trials (D = -9.87 + 0.71 * [SD of lateral head-ball angle] + 21.73 * [timing of saccade to ball-bounce]; F = 6.65; df 2, 45; p = .003; group centroids: outswing = -0.56; inswing = 0.51). Out-swinging trials were associated with a more consistent lateral head-ball angle and an earlier saccade to ball-bounce. The model accurately predicted group memberships for 70.8% of cases with 69.6% of outswing and 72.0% of inswing trials categorised correctly. Cross validation revealed that the successful classification of straight and swinging trials did not change.

Discussion

As expected, interceptive performance was significantly worse in trials where the ball swung away from, as opposed to in towards the batter, and there was some suggestion that this difference could at least in part be explained by more novice-like gaze behaviour. In particular, gaze lagged further behind the ball when the ball swung away from the batter, and this reduced the proportion of ball-flight in which gaze was located ahead of the ball. However, there were no differences in any of the other key markers of expertise (i.e., no difference in the likelihood of saccades towards ball-bounce or bat-ball contact, or in the likelihood of co-aligning gaze with the ball at the moment of bat-ball contact). In fact, the discriminant function analysis revealed that one of the two best discriminators of gaze was the timing of the saccades to ball-bounce, surprisingly revealing *earlier* saccades when facing the out-swinging trials. This finding is in direct contrast to the assumption that earlier saccades are associated with better interceptive performance (e.g., Land & McLeod, 2000). In this case, earlier saccades were associated with *poorer* interceptive performance.

It is not immediately clear why out-swinging trajectories result in earlier saccades, although the results for the lateral positions of the head and gaze relative to the ball may provide a clue, and help to explain the difficulties experienced when the ball swings away. The directions of gaze and the head were more closely orientated towards the ball in the lateral direction when facing the out-swinging deliveries (as evidenced by the mean lateral gaze-ball angle, and the mean and SD of lateral head-ball angle). This better lateral alignment is likely to be a reflection of the decrease in lateral movements necessary to follow the out-swinging ball. Out-swinging trials generally follow a more head-on trajectory on their path towards the batter (Sarpeshkar, et al., 2017), with the ball more likely to travel along the mid-sagittal plane of the direction in which the batter is facing. Balls that follow a more head-on trajectory have previously been shown to increase the difficulty with which the observer can detect both the approach angle of the ball (Welchman, et al., 2004) and the rate at which the ball is deviating laterally (Diaz, et al., 2009). This may have resulted in the batters being deceived into thinking that the ball was following a straight rather than swinging trajectory, leading them to perform earlier, though ultimately incorrect saccades. Evidently, the ball did swing on those trials, and performance was markedly worse.

Finally, the manner in which the direction of curvature interacts with the *stance* of the batter may provide an interesting avenue for future work that seeks to better understand the impact of the different directions of curvature on interceptive performance. In this study, we have defined an 'outswing' trajectory as one that moves progressively away from the batter's body, irrespective of whether they adopt a 'right-handed' or 'left-handed' stance. That is, a ball that follows an 'outswing' trajectory to a batter who adopts a right-handed stance would represent an 'inswing' trajectory to a batter in a left-handed stance. We have not, in this study, examined the separate impact of the direction of swing on those who adopt a right or left handed stance. But given the surprising over-representation of batters who adopt a left-handed stance at the elite level when batting (Mann, Runswick, & Allen, 2016; Wood & Aggleton, 1989), it could be that the more obtuse angle from which the ball will most commonly approach a batter in a left-handed stance will alter the heading direction, and help to make the direction of swing more obvious to the batter. That is to say, left-handers could have an inherent advantage whereby the direction of swing is more obvious to them. Most bowlers do not change the position from which they release the ball when bowling to a left-handed batter, and so the ball must move across their body (from right to left in Figure 1a), potentially negating the more head-on trajectory that a right-handed batter would experience when facing an out-swinging delivery. If this were to be true, then the disadvantage that right handed batters have when facing an out-swing (when compared to in-swing) delivery might be negated, or at least diminished, for left-handed batters.

General Discussion

The aim of this study was to perform a comprehensive examination of the eye and head movement strategies that underpin the development of visual-motor expertise when performing a fast-paced interceptive action. The flight-path of a cricket ball was manipulated so that batters of different levels of skill and age attempted to hit balls that followed either a straight or a curving flight-path. The initial findings against straight trajectories provided support for only some of the existing and widely cited markers of visual-motor expertise that have been found largely on the basis of case-study designs (*viz*. directing gaze ahead of the ball, predictive saccades towards bat-ball contact, and maintaining gaze at contact when hitting the ball). In particular, the results from this study on a population level failed to support the claim that skilled batters perform earlier saccades, or that they are better able to egocentrically track the location of the ball, highlighting the limitations of previous studies in accurately representing the visual-motor behaviour of the wider population. Those differences that were found as a result of skill emerged by late adolescence and continued into adulthood, demonstrating that these skills hold promise as a measure of talent identification.

Curving trajectories significantly alter the visual-motor behaviour of all batters, generally resulting in gaze that would be considered to be more 'novice-like'. A considerable proportion of the changes as a result of curving trajectories can be explained by the increased uncertainty that is present when there is a possibility of ball-swing. This led to a significant reduction in both batting performance, and the predictive ability of the batters, highlighting the top-down influence of expectations on visual-motor behaviour. When the ball did swing, there was a further decrease in interceptive performance, and some associated changes in gaze that would also be considered more novice-like. However, ball-swing also resulted in functional adaptations that included better gaze-ball alignment, and the use of oblique saccades. Performance was worse when intercepting trajectories that curved *away* from the observer, but surprisingly, was associated with *earlier* predictive saccades. This suggests that the relationship between performance and earlier predictions may not be a linear one, and that the role of predictive saccades may be more complex than has been previously assumed. Crucially, when the ball swung, these new visual-motor markers of expertise were found in addition to differences for other existing markers typically found against straight trajectories, suggesting that interception in the presence of ball-swing may provide a more sensitive measure for differentiating skill in batting.

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Table 1. *Descriptive Statistics (M ± SD) when Intercepting Blocked-Straight Trials as a function of Skill, Age, and Ball-length*

		Across all ball-lengths		**Full-length**		**Good-length**		**Short-length**	
		Adult	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**
Batting performance									
%Good Bat-ball contacts	Elite	90.4 ± 16.4	85.6 ± 16.9	86.5 ± 13.2	73.7 ± 23.6	91.7 ± 16.7	92.2 ± 12.5	93.1 ± 90.7	90.7 ± 14.7
	Club	64.7 ± 31.0	63.3 ± 31.0	63.3 ± 28.2	54.8 ± 32.9	72.5 ± 20.8	73.3 ± 22.5	58.3 ± 43.9	61.7 ± 37.5
%High FoBS	Elite	47.8 ± 27.6	49.6 ± 28.8	66.0 ± 20.2	79.6 ± 16.7	18.6 ± 24.3	28.9 ± 38.2	58.8 ± 38.3	40.4 ± 32.6
	Club	35.4 ± 24.4	54.6 ± 30.1	65.2 ± 18.7	77.3 ± 24.0	12.5 ± 27.0	27.2 ± 32.4	28.7 ± 27.4	59.2 ± 33.8
Gaze and head position (deg)									
Gaze-Ball angle	Elite	-0.1 ± 1.7	-1.2 ± 1.4	-0.5 ± 1.9	-0.8 ± 1.3	0.9 ± 1.9	-0.5 ± 1.1	-0.6 ± 1.5	-2.1 ± 1.8
	Club	0.6 ± 1.9	0.1 ± 1.9	1.0 ± 2.0	0.2 ± 1.9	0.7 ± 2.2	0.9 ± 1.8	0.2 ± 1.4	-0.7 ± 2
SD Gaze-Ball angle	Elite	3.7 ± 2.5	3.7 ± 2.3	4.2 ± 3.4	2.6 ± 1.7	3.6 ± 2.6	3.1 ± 2.3	3.2 ± 1.4	5.4 ± 2.9
	Club	4.8 ± 2.6	3.5 ± 2.1	4.6 ± 2.2	3.2 ± 2.2	5.5 ± 2.7	3.3 ± 2.0	4.3 ± 3.0	3.9 ± 2.2
Gaze-Head angle	Elite	-3.3 ± 2.1	-3.6 ± 2.4	-3.1 ± 2.4	-2.0 ± 3.1	-3.3 ± 1.6	-3.6 ± 1.6	-3.4 ± 2.3	-5.1 ± 2.5
	Club	-3.7 ± 2.3	-3.2 ± 1.4	-2.6 ± 2.9	-2.3 ± 1.8	-3.4 ± 2.0	-2.9 ± 1.0	-4.9 ± 1.9	-4.3 ± 1.3
SD Gaze-Head angle	Elite	4.0 ± 1.9	5.4 ± 2.5	4.8 ± 2.7	4.6 ± 2.7	3.7 ± 1.8	5.0 ± 2.0	3.4 ± 1.2	6.5 ± 2.7
	Club	4.3 ± 2.6	4.4 ± 2.1	4.0 ± 2.8	4.2 ± 2.6	4.0 ± 2.9	3.3 ± 1.4	4.9 ± 2.0	5.7 ± 2.3
Head-Ball angle	Elite	3.4 ± 2.3	2.8 ± 2.2	2.9 ± 2.7	1.8 ± 2.9	4.3 ± 2.3	3.4 ± 2.1	2.9 ± 2.1	3.0 ± 1.5
	Club	4.3 ± 2.6	3.2 ± 2.0	3.5 ± 2.8	2.4 ± 2.3	4.6 ± 2.9	3.7 ± 1.9	4.7 ± 2.5	3.4 ± 1.8
SD Head-Ball angle	Elite	4.9 ± 3.2	3.6 ± 2.3	6.3 ± 3.8	4.1 ± 3.7	5.7 ± 3.8	4.3 ± 2.2	2.8 ± 2.0	2.4 ± 16.0
	Club	4.8 ± 2.9	3.8 ± 2.0	5.3 ± 2.9	4.5 ± 2.5	5.5 ± 3.7	4.3 ± 2.3	3.6 ± 2.1	2.7 ± 1.0
% $Gaze_{ahead}$	Elite	53.0 ± 26.4	57.7 ± 24.5	61.5 ± 24.9	60.7 ± 28.7	47.8 ± 26.5	50.8 ± 20.9	49.7 ± 27.7	61.6 ± 24.0
	Club	45.3 ± 22.2	47.6 ± 30.1	44.5 ± 24.4	59.2 ± 31.1	41.2 ± 20.6	40.5 ± 33.6	50.1 ± 21.8	43.0 ± 25.6

Table 1 continued.

		Across all ball-lengths		Full-length		Good-length		Short-length	
		Adult	Youth	Adult	Youth	Adult	Youth	Adult	Youth
Gaze at bat-ball contact									
%$BBC_{contact}$	Elite	41.3 ± 32.3	51.0 ± 30.1	34.1 ± 33.8	41.9 ± 35.9	26.1 ± 24.3	24.1 ± 34.5	63.6 ± 38.8	87.0 ± 20.0
	Club	26.0 ± 39.5	26.2 ± 25.8	25.6 ± 32.7	21.1 ± 26.6	25.9 ± 43.4	8.2 ± 16.3	26.7 ± 42.4	49.4 ± 34.6
%$BBC_{lagging}$	Elite	26.3 ± 24.5	30.9 ± 29.5	29.6 ± 25.1	33.3 ± 31.2	40.3 ± 26.8	53.7 ± 40.6	9.1 ± 21.6	5.6 ± 16.7
	Club	49.9 ± 45.6	50.0 ± 32.7	48.5 ± 40.9	44.4 ± 34.6	52.4 ± 45.8	73.9 ± 28.3	48.9 ± 50.1	31.7 ± 35.1
%$BBC_{Post\text{-}contact}$	Elite	31.4 ± 30.6	18.1 ± 27.9	36.4 ± 31.5	24.8 ± 31.6	33.6 ± 25.5	22.2 ± 37.3	24.2 ± 34.7	7.4 ± 14.7
	Club	24.0 ± 40.2	23.8 ± 30.5	25.9 ± 42.6	34.4 ± 33.2	21.7 ± 38.4	18.0 ± 25.8	24.4 ± 39.7	18.9 ± 32.5
Type of saccades (%)									
Saccade towards ball-bounce	Elite	46.2 ± 33.0	49.2 ± 37.7	65.6 ± 29.6	63.0 ± 32.9	36.9 ± 36.2	38.3 ± 39.3	36.2 ± 33.3	46.3 ± 40.9
	Club	56.2 ± 45.4	34.2 ± 33.6	61.7 ± 44.5	46.3 ± 40.0	52.0 ± 46.7	26.8 ± 23.9	54.8 ± 45.1	29.5 ± 37.8
Saccade towards bat-ball contact	Elite	20.9 ± 21.4	28.8 ± 25.3	0 ± 0	1.7 ± 5.3	19.0 ± 28.0	23.3 ± 33.5	43.9 ± 36.3	61.3 ± 37.3
	Club	13.3 ± 24.2	9.3 ± 14.9	0 ± 0	0 ± 0	22.5 ± 35.2	6.5 ± 14.2	17.5 ± 37.4	19.3 ± 25.0
Timing of saccade (following ball-release; ms)									
Saccade towards ball-bounce	Elite	329 ± 42	325 ± 37	414 ± 34	399 ± 29	343 ± 67	343 ± 40	229 ± 25	234 ± 43
	Club	315 ± 52	316 ± 54	394 ± 42	416 ± 27	274 ± 49	319 ± 96	275 ± 65	212 ± 39
Saccade towards bat-ball contact	Elite	407 ± 38	378 ± 36			500 ± 47	438 ± 28	492 ± 41	461 ± 37
	Club	436 ± 22	473 ± 12			445 ± 25	470 ± 14	427 ± 19	476 ± 9

Table 2. *Descriptive Statistics (M ± SD) when Intercepting Blocked-Straight and Random-Straight Trials as a function of Skill, Age, and Ball-length*

		Full-length				Good-length			
		Blocked-Straight		**Random-Straight**		**Blocked-Straight**		**Random-Straight**	
		Adult	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**
Batting performance									
%Good bat-ball contacts	Elite	85.1 ± 12.5	74.7 ± 22.5	68.3 ± 18.2	66.6 ± 30.6	91.7 ± 16.7	93.0 ± 12.0	80.2 ± 18.6	72.5 ± 10.6
	Club	63.3 ± 28.2	54.8 ± 32.9	62.8 ± 26.1	59.7 ± 34.0	72.5 ± 20.8	73.3 ± 22.5	80.5 ± 18.4	71.6 ± 23.1
%High FoBS	Elite	69.3 ± 22.3	80.0 ± 14.8	71.5 ± 27.0	73.0 ± 19.3	19.7 ± 24.7	26.0 ± 37.1	24.5 ± 30.0	13.7 ± 21.8
	Club	65.2 ± 18.7	77.3 ± 24.0	58.5 ± 31.9	64.0 ± 31.8	12.5 ± 27.0	27.2 ± 32.4	9.5 ± 17.1	13.7 ± 18.8
Gaze and Head position (deg)									
Gaze-Ball angle	Elite	-0.5 ± 1.9	-0.7 ± 1.3	0.9 ± 1.5	-0.7 ± 1.1	0.6 ± 2.0	-0.3 ± 1.2	0.9 ± 1.9	0.3 ± 1.6
	Club	1.0 ± 2.0	0.2 ± 1.9	1.2 ± 1.6	0.5 ± 1.6	0.7 ± 2.2	0.9 ± 1.8	1.9 ± 1.6	0.6 ± 1.5
SD Gaze-Ball angle	Elite	4.3 ± 3.2	2.9 ± 1.9	3.4 ± 2.3	2.8 ± 1.8	3.5 ± 2.4	3.2 ± 2.2	3.0 ± 2.0	3.2 ± 2.5
	Club	4.6 ± 2.2	3.2 ± 2.2	3.7 ± 2.1	3.2 ± 2.0	5.5 ± 2.7	3.3 ± 2.0	3.9 ± 1.6	2.5 ± 1.8
Gaze-Head angle	Elite	-3.3 ± 2.3	-2.4 ± 3.1	-2.5 ± 2.3	-3.2 ± 2.9	-3.5 ± 1.6	-3.5 ± 1.6	-2.7 ± 2.3	-3.1 ± 2.3
	Club	-2.6 ± 2.9	-2.3 ± 1.8	-2.7 ± 2.7	-2.3 ± 2.2	-3.4 ± 1.9	-2.9 ± 1.0	-2.4 ± 2.3	-2.9 ± 1.8
SD Gaze-Head angle	Elite	5.0 ± 2.5	5.0 ± 2.8	4.1 ± 2.5	5.0 ± 2.4	3.9 ± 1.9	4.9 ± 1.9	3.4 ± 2.0	4.5 ± 2.4
	Club	4.0 ± 2.8	4.2 ± 2.6	3.4 ± 2.4	4.1 ± 2.5	4.0 ± 2.9	3.3 ± 1.4	2.7 ± 1.5	3.6 ± 2.1
Head-Ball angle	Elite	3.0 ± 2.6	2.2 ± 3.0	3.5 ± 1.6	3.0 ± 3.2	4.2 ± 2.3	3.7 ± 2.2	3.7 ± 1.5	2.9 ± 2.1
	Club	3.5 ± 2.8	2.3 ± 2.3	4.0 ± 3.4	2.9 ± 2.5	4.6 ± 2.9	3.7 ± 2.2	4.4 ± 3.1	3.6 ± 2.3
SD Head-Ball angle	Elite	6.2 ± 3.9	4.6 ± 3.9	6.1 ± 2.7	5.2 ± 4.2	5.3 ± 3.9	4.7 ± 2.5	4.7 ± 2.3	3.6 ± 2.2
	Club	5.3 ± 2.9	4.5 ± 2.5	5.5 ± 3.6	4.8 ± 3.1	5.5 ± 3.7	4.3 ± 2.3	4.7 ± 2.9	4.6 ± 2.6
% $Gaze_{ahead}$	Elite	61.5 ± 24.9	61.1 ± 27.1	43.1 ± 24.7	59.3 ± 29.8	45.3 ± 24.8	49.9 ± 19.9	35.5 ± 26.1	46.9 ± 21.2
	Club	44.5 ± 24.4	59.2 ± 31.1	47.4 ± 23.8	50.4 ± 28.7	41.2 ± 20.6	40.5 ± 33.6	34.5 ± 17.5	49.7 ± 30.8
Lateral Gaze-Ball angle	Elite	1.0 ± 1.6	0.3 ± 0.5	0.5 ± 1.1	0.2 ± 0.7	0.5 ± 0.9	0.0 ± 0.5	0.5 ± 0.8	0.4 ± 0.9
	Club	0.7 ± 1.3	0.5 ± 1.3	0.9 ± 1.0	0.2 ± 0.8	0.7 ± 1.7	0.6 ± 0.4	0.9 ± 1.4	0.2 ± 1.0
SD lateral Gaze-Ball angle	Elite	2.0 ± 2.2	1.0 ± 0.4	1.3 ± 1.2	0.9 ± 0.7	1.1 ± 0.7	1.0 ± 0.6	1.0 ± 0.7	1.1 ± 0.9
	Club	1.7 ± 2.0	1.7 ± 2.2	1.7 ± 1.7	1.4 ± 1.1	2.8 ± 2.7	1.2 ± 0.8	1.2 ± 1.1	1.3 ± 1.4
Lateral Gaze-Head angle	Elite	0.0 ± 1.8	0.0 ± 1.3	0.0 ± 2.1	0.1 ± 1.4	-0.3 ± 2.3	0.0 ± 1.8	-0.1 ± 2.2	0.0 ± 1.5
	Club	-0.2 ± 2.0	0.0 ± 1.5	0.3 ± 2.1	0.1 ± 1.3	-0.2 ± 2.5	0.4 ± 0.9	0.2 ± 2.1	-0.1 ± 1.3
SD lateral Gaze-Head angle	Elite	2.8 ± 2.8	1.3 ± 0.6	1.6 ± 0.9	1.5 ± 0.8	2.6 ± 2.3	2.3 ± 1.4	1.7 ± 1.0	1.8 ± 1.3
	Club	2.2 ± 1.8	2.1 ± 2.3	2.4 ± 1.9	2.1 ± 1.5	2.6 ± 2.0	1.9 ± 0.9	1.6 ± 1.1	1.3 ± 1.5
Lateral Head-Ball angle	Elite	1.4 ± 2.4	0.3 ± 1.4	0.7 ± 1.8	0.0 ± 1.3	0.8 ± 2.2	0.1 ± 1.4	0.7 ± 1.8	0.4 ± 1.2
	Club	0.8 ± 1.1	0.5 ± 0.7	0.5 ± 1.0	0.5 ± 0.9	0.8 ± 1.6	0.2 ± 0.6	0.5 ± 0.9	0.3 ± 0.8
SD lateral Head-Ball angle	Elite	2.1 ± 2.4	1.3 ± 1.0	1.9 ± 1.5	1.4 ± 0.8	2.2 ± 1.8	1.5 ± 0.7	1.7 ± 1.1	1.2 ± 0.5
	Club	1.6 ± 0.9	1.0 ± 0.4	1.3 ± 0.7	1.0 ± 0.8	2.3 ± 2.3	1.1 ± 0.4	1.2 ± 0.6	0.7 ± 0.6

Table 2 continued.

Gaze at bat-ball contact									
%BBC$_{contact}$	Elite	38.6 ± 34.6	39.7 ± 34.6	10.9 ± 11.9	32.0 ± 26.3	29.1 ± 22.8	29.2 ± 36.3	21.0 ± 30.3	14.6 ± 16.5
	Club	25.6 ± 32.7	26.7 ± 36.7	14.4 ± 26.1	20.4 ± 28.5	25.9 ± 43.4	10.9 ± 16.8	14.8 ± 27.2	5.0 ± 10.0
%BBC$_{lagging}$	Elite	25.0 ± 25.6	32.0 ± 29.7	59.1 ± 21.8	45.2 ± 29.1	41.8 ± 25.8	50.8 ± 39.4	58.1 ± 27.6	73.7 ± 22.7
	Club	48.5 ± 40.9	44.4 ± 34.6	61.7 ± 38.6	53.5 ± 26.3	52.4 ± 45.8	74.8 ± 28.2	69.6 ± 30.5	91.8 ± 12.4
%BBC$_{Post\text{-}Contact}$	Elite	36.4 ± 31.5	28.3 ± 31.8	30.0 ± 24.9	22.7 ± 22.2	29.1 ± 19.6	20.0 ± 35.8	20.9 ± 22.9	11.7 ± 24.9
	Club	25.9 ± 42.6	28.9 ± 34.4	23.9 ± 35.0	26.1 ± 18.9	21.7 ± 38.4	14.3 ± 25.8	15.6 ± 24.7	3.2 ± 9.5
Type of saccades (%)									
Saccade towards ball-bounce	Elite	60.3 ± 31.6	52.7 ± 36.5	59.8 ± 30.2	65.9 ± 24.2	36.9 ± 36.2	38.3 ± 39.3	28.2 ± 33.2	32.8 ± 18.4
	Club	48.3 ± 46.1	34.7 ± 35.6	34.2 ± 36.9	33.9 ± 25.6	49.5 ± 46.0	24.8 ± 25.3	31.3 ± 37.6	15.4 ± 26.2
Saccade towards bat-ball contact	Elite	0 ± 0	1.7 ± 5.3	0 ± 0	1.4 ± 4.5	19.0 ± 28.0	23.3 ± 33.5	10.9 ± 22.4	17.2 ± 18.2
	Club	0 ± 0	0 ± 0	0 ± 0	0 ± 0	22.5 ± 35.1	6.5 ± 14.2	0 ± 0	0 ± 0
Oblique saccade towards ball-bounce	Elite	5.4 ± 8.4	10.3 ± 26.4	3.2 ± 6.0	8.3 ± 21.2	0 ± 0	0 ± 0	0 ± 0	0 ± 0
	Club	13.3 ± 24.6	11.7 ± 25.2	7.9 ± 21.0	6.3 ± 10.7	2.5 ± 7.9	4.0 ± 8.4	5.0 ± 15.8	3.9 ± 8.7
Timing of saccade (following ball-release; ms)									
Saccade towards ball-bounce	Elite	414 ± 34	399 ± 29	415 ± 29	398 ± 25	343 ± 67	343 ± 40	362 ± 41	383 ± 43
	Club	394 ± 42	416 ± 27	413 ± 19	420 ± 23	274 ± 49	319 ± 96	369 ± 57	387 ± 27
Saccade towards bat-ball contact	Elite					500 ± 47	438 ± 28	467 ± 31	437 ± 27
	Club					445 ± 25	470 ± 14		
Oblique saccade towards ball-bounce	Elite			453 ± 23	415 ± 35				
	Club			450 ± 42	360 ± 106				340 ± 85

Table 3. *Descriptive Statistics (M ± SD) when Intercepting Random-Straight and Swinging Trials as a function of Skill, Age, and Ball-length.*

		Full-length				Good-length			
		Random-Straight		**Swinging**		**Random-Straight**		**Swinging**	
		Adult	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**
Batting performance									
%Good bat-ball contact	Elite	68.4 ± 18.2	66.6 ± 30.6	57.7 ± 11.8	51.1 ± 15.3	80.2 ± 18.6	72.6 ± 10.6	62.2 ± 14.0	56.8 ± 30.0
	Club	62.8 ± 26.1	59.7 ± 34.0	27.4 ± 11.9	33.1 ± 15.3	80.5 ± 18.4	71.6 ± 23.1	59.6 ± 30.6	55.9 ± 31.1
%High FoBS	Elite	71.5 ± 27.0	73.1 ± 19.3	64.5 ± 22.6	58.5 ± 33.0	24.5 ± 30.0	13.7 ± 21.8	20.2 ± 21.6	19.3 ± 17.5
	Club	58.5 ± 31.9	64.0 ± 31.8	50.5 ± 34.8	40.1 ± 32.8	9.5 ± 17.1	13.7 ± 21.8	18.3 ± 17.9	30.9 ± 18.4
Gaze and Head position (deg)									
Gaze-Ball angle	Elite	1.1 ± 1.4	-0.7 ± 1.1	0.4 ± 0.9	-0.5 ± 1.1	1.2 ± 1.5	0.3 ± 1.6	0.7 ± 1.0	0.0 ± 1.0
	Club	1.2 ± 1.6	0.5 ± 1.6	1.3 ± 2.4	1.3 ± 2.9	1.9 ± 1.6	0.6 ± 1.5	2.0 ± 1.9	0.7 ± 1.3
SD Gaze-Ball angle	Elite	3.4 ± 2.4	2.8 ± 1.9	2.8 ± 0.9	2.8 ± 1.4	2.8 ± 2.1	3.2 ± 2.5	2.2 ± 0.9	3.8 ± 2.5
	Club	4.0 ± 1.8	3.2 ± 2.0	5.1 ± 2.2	4.0 ± 3.5	4.2 ± 1.5	2.5 ± 1.8	4.6 ± 1.5	2.5 ± 1.4
Gaze-Head angle	Elite	-2.3 ± 2.4	-3.2 ± 2.9	-1.8 ± 1.9	-2.4 ± 2.6	-2.2 ± 1.8	-3.1 ± 2.3	-1.8 ± 1.7	-2.9 ± 2.3
	Club	-3.0 ± 2.7	-2.3 ± 2.2	-2.9 ± 2.7	-2.1 ± 1.7	-2.8 ± 2.1	-2.9 ± 1.8	-2.5 ± 2.2	-2.5 ± 1.3
SD Gaze-Head angle	Elite	4.1 ± 2.6	5.0 ± 2.4	3.7 ± 1.4	4.0 ± 2.0	3.0 ± 1.6	4.5 ± 2.4	3.0 ± 0.9	4.4 ± 2.5
	Club	3.7 ± 2.4	4.1 ± 2.5	3.9 ± 2.3	3.4 ± 1.7	2.8 ± 1.6	3.6 ± 2.1	2.8 ± 1.3	3.0 ± 1.5
Head-Ball angle	Elite	3.5 ± 1.7	3.0 ± 3.2	2.4 ± 1.8	2.1 ± 2.5	3.6 ± 1.6	2.9 ± 2.1	2.5 ± 1.1	3.2 ± 2.4
	Club	4.5 ± 3.4	2.9 ± 2.8	4.3 ± 3.1	3.4 ± 2.7	4.9 ± 2.9	3.6 ± 2.3	4.6 ± 2.6	3.3 ± 1.7
SD Head-Ball angle	Elite	6.4 ± 2.7	5.2 ± 4.2	4.6 ± 2.3	3.5 ± 2.4	4.8 ± 2.4	3.6 ± 2.2	3.4 ± 1.5	3.8 ± 2.5
	Club	6.1 ± 3.5	4.8 ± 3.1	5.4 ± 2.7	5.0 ± 3.5	5.2 ± 2.6	4.6 ± 2.6	4.4 ± 2.1	4.0 ± 2.1
% $Gaze_{ahead}$	Elite	42.9 ± 25.9	59.3 ± 29.8	48.5 ± 24.8	63.3 ± 25.3	31.9 ± 24.1	46.9 ± 21.2	33.1 ± 23.5	49.4 ± 16.9
	Club	49.0 ± 24.7	50.4 ± 28.7	46.8 ± 23.1	53.2 ± 24.1	35.8 ± 18.0	49.7 ± 30.8	35.6 ± 18.9	50.9 ± 23.4
Lateral Gaze-Ball angle	Elite	0.5 ± 1.2	0.2 ± 0.7	0.4 ± 0.9	0.4 ± 0.7	0.4 ± 0.9	0.4 ± 0.9	0.5 ± 0.8	0.3 ± 0.8
	Club	0.9 ± 1.0	0.2 ± 0.8	0.9 ± 1.5	0.1 ± 0.9	0.9 ± 1.5	0.2 ± 1.0	0.4 ± 1.7	0.3 ± 1.0
SD lateral Gaze-Ball angle	Elite	1.4 ± 1.3	0.9 ± 0.7	1.5 ± 0.9	1.2 ± 0.7	0.9 ± 0.7	1.1 ± 0.9	0.9 ± 0.4	0.9 ± 0.4
	Club	1.8 ± 1.8	1.4 ± 1.1	2.3 ± 1.3	1.5 ± 1.2	1.3 ± 1.1	1.3 ± 1.4	2.1 ± 1.4	1.1 ± 0.6
Lateral Gaze-Head angle	Elite	0.2 ± 2.1	0.1 ± 1.4	-0.3 ± 2.2	0.2 ± 0.3	-0.1 ± 2.3	0.0 ± 1.5	-0.2 ± 2.3	0.5 ± 1.8
	Club	0.3 ± 2.3	0.1 ± 1.3	0.2 ± 1.9	-0.1 ± 1.2	0.2 ± 2.3	-0.1 ± 1.4	0.0 ± 2.1	0.0 ± 1.5
SD lateral Gaze-Head angle	Elite	1.7 ± 0.9	1.5 ± 0.8	2.3 ± 1.0	1.5 ± 0.7	1.7 ± 1.1	1.8 ± 1.3	2.0 ± 1.3	1.9 ± 0.9
	Club	2.6 ± 1.9	2.1 ± 1.5	2.2 ± 1.1	1.7 ± 1.0	1.8 ± 1.1	1.3 ± 1.5	1.9 ± 0.9	1.5 ± 1.0
Lateral Head-Ball angle	Elite	0.6 ± 1.9	0.0 ± 1.3	0.8 ± 2.0	0.3 ± 1.1	0.7 ± 1.9	0.4 ± 1.2	0.7 ± 1.8	0.0 ± 1.2
	Club	0.5 ± 1.1	0.6 ± 0.9	0.7 ± 1.0	0.3 ± 1.0	0.5 ± 0.9	0.3 ± 0.8	0.4 ± 1.0	0.3 ± 1.0
SD lateral Head-Ball angle	Elite	2.0 ± 1.5	1.4 ± 0.8	2.3 ± 1.1	1.6 ± 0.5	1.7 ± 1.1	1.2 ± 0.5	1.6 ± 1.0	1.6 ± 0.5
	Club	1.4 ± 0.7	1.0 ± 0.8	2.0 ± 0.6	1.7 ± 1.1	1.3 ± 0.5	0.7 ± 0.6	2.0 ± 1.3	1.2 ± 0.5

Table 3 continued.

					Gaze at bat-ball contact				
$\%BBC_{contact}$	Elite	10.0 ± 11.8	32.0 ± 26.3	16.1 ± 20.9	26.2 ± 22.1	19.3 ± 29.5	14.6 ± 16.5	13.2 ± 12.3	22.2 ± 27.0
	Club	14.4 ± 26.1	20.4 ± 28.5	9.4 ± 13.5	8.2 ± 10.4	14.8 ± 27.2	5.0 ± 10.0	5.2 ± 15.6	10.1 ± 14.0
$\%BBC_{lagging}$	Elite	62.6 ± 23.9	45.2 ± 29.1	57.4 ± 24.0	52.5 ± 17.4	61.6 ± 28.9	73.7 ± 22.7	66.1 ± 19.8	67.0 ± 22.5
	Club	61.8 ± 38.6	53.5 ± 26.3	60.3 ± 30.5	82.3 ± 8.1	69.6 ± 30.5	91.8 ± 12.5	75.6 ± 21.9	75.4 ± 16.7
$\%BBC_{Post\text{-}Contact}$	Elite	27.5 ± 25.3	22.7 ± 22.2	26.5 ± 22.4	21.3 ± 18.5	19.1 ± 22.6	11.7 ± 24.9	20.8 ± 24.8	10.8 ± 13.8
	Club	23.9 ± 35.0	26.1 ± 18.9	30.3 ± 30.1	9.5 ± 10.0	15.6 ± 24.7	3.2 ± 9.5	20.3 ± 16.7	14.5 ± 20.3
					Type of saccades (%)				
Saccade towards ball-bounce	Elite	59.8 ± 30.2	65.9 ± 24.3	40.4 ± 20.0	49.8 ± 28.5	28.2 ± 33.3	32.8 ± 18.4	30.3 ± 23.9	33.6 ± 24.8
	Club	34.2 ± 37.0	33.9 ± 25.6	35.5 ± 35.9	27.5 ± 25.5	31.3 ± 37.6	15.4 ± 26.2	29.1 ± 38.3	21.8 ± 19.5
Saccade towards bat-ball contact	Elite	0 ± 0	1.4 ± 4.5	0.5 ± 1.7	1.5 ± 3.1	10.9 ± 22.4	17.2 ± 18.2	2.0 ± 3.8	11.7 ± 13.0
	Club	0 ± 0	0 ± 0	0.8 ± 2.6	0 ± 0	0 ± 0	0 ± 0	2.5 ± 7.9	3.3 ± 5.5
Oblique saccade towards ball-bounce	Elite	3.2 ± 6.0	8.3 ± 21.2	12.0 ± 11.4	16.2 ± 18.6	0 ± 0	0 ± 0	2.8 ± 6.9	1.9 ± 4.2
	Club	7.9 ± 21.0	6.3 ± 10.7	14.7 ± 20.3	4.9 ± 9.4	5.0 ± 15.8	3.9 ± 8.7	3.3 ± 10.5	4.3 ± 10.7
					Timing of saccade (following ball-release; ms)				
Saccade towards ball-bounce	Elite	415 ± 29	398 ± 25	426 ± 23	405 ± 22	362 ± 41	383 ± 43	402 ± 37	368 ± 24
	Club	413 ± 19	420 ± 23	395 ± 38	419 ± 18	369 ± 57	387 ± 27	360 ± 32	392 ± 33
Saccade towards bat-ball contact	Elite								
	Club								
Oblique saccade towards ball-bounce	Elite	453 ± 23	415 ± 35	423 ± 15	423 ± 35				
	Club	450 ± 42	360 ± 106	422 ± 2			340 ± 85		

Table 4. *Descriptive Statistics (M ± SD) when Intercepting the Out-swing and In-swing Trials as a function of Skill, Age, and Ball-length.*

		Full-length				**Good-length**			
		Out-swing		**In-swing**		**Out-swing**		**In-swing**	
		Adult	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**	**Adult**	**Youth**
Batting performance									
%Good bat-ball contact	Elite	60.2 ± 23.7	41.5 ± 30.4	47.6 ± 24.4	60.6 ± 16.3	51.7 ± 28.3	53.3 ± 44.3	77.4 ± 23.4	60.3 ± 35.6
	Club	12.3 ± 20.3	20.8 ± 28.7	42.5 ± 36.3	45.3 ± 27.3	56.7 ± 41.7	41.7 ± 44.6	62.5 ± 33.2	70.2 ± 26.3
%High FoBS	Elite	58.6 ± 34.4	46.7 ± 44.3	73.9 ± 24.2	70.4 ± 32.0	20.0 ± 22.7	15.8 ± 27.3	19.4 ± 30.0	22.7 ± 18.9
	Club	38.5 ± 46.4	34.2 ± 39.0	62.5 ± 38.5	46.0 ± 32.3	0 ± 0	23.3 ± 32.4	36.7 ± 35.8	38.5 ± 37.2
Gaze and Head position (deg)									
Gaze-Ball angle	Elite	0.6 ± 0.9	-0.1 ± 1.5	0.0 ± 1.2	-0.8 ± 1.3	0.9 ± 1.1	0.6 ± 1.8	0.3 ± 1.1	-0.6 ± 1.3
	Club	1.7 ± 2.8	1.4 ± 2.7	0.9 ± 2.3	1.1 ± 3.4	2.0 ± 1.7	0.9 ± 1.5	1.9 ± 2.4	0.6 ± 1.2
SD Gaze-Ball angle	Elite	2.7 ± 1.6	3.1 ± 2.1	2.6 ± 1.5	2.5 ± 1.4	2.5 ± 1.9	3.7 ± 3.7	2.1 ± 1.3	3.8 ± 2.2
	Club	5.4 ± 3.1	3.9 ± 3.4	4.9 ± 2.1	4.2 ± 4.5	3.8 ± 1.9	2.4 ± 1.7	5.3 ± 2.1	2.7 ± 1.4
Gaze-Head angle	Elite	-1.8 ± 2.2	-2.3 ± 2.9	-1.7 ± 1.8	-2.4 ± 2.3	-1.7 ± 1.7	-2.8 ± 2.7	-1.7 ± 1.7	-3.1 ± 2.2
	Club	-2.8 ± 2.9	-2.3 ± 1.4	-3.1 ± 2.5	-2.0 ± 2.1	-2.1 ± 2.5	-2.4 ± 1.1	-3.0 ± 2.3	2.7 ± 1.8
SD Gaze-Head angle	Elite	3.2 ± 1.9	4.2 ± 2.4	3.7 ± 2.2	3.8 ± 2.1	2.6 ± 1.0	3.8 ± 2.7	3.2 ± 1.0	5.0 ± 2.9
	Club	3.9 ± 2.6	3.4 ± 1.6	3.8 ± 2.5	3.4 ± 2.3	2.6 ± 1.2	2.7 ± 1.4	3.1 ± 2.0	3.3 ± 1.9
Head-Ball angle	Elite	2.4 ± 2.2	2.3 ± 2.7	1.8 ± 1.9	1.9 ± 2.3	2.6 ± 1.2	3.2 ± 2.7	2.1 ± 1.6	3.1 ± 2.3
	Club	4.6 ± 3.5	3.7 ± 3.0	4.1 ± 2.8	3.2 ± 2.7	4.3 ± 2.7	3.2 ± 1.9	4.9 ± 2.7	3.3 ± 1.9
SD Head-Ball angle	Elite	4.8 ± 3.0	3.5 ± 2.9	3.8 ± 2.3	3.5 ± 2.2	3.8 ± 2.3	3.9 ± 3.3	3.2 ± 1.7	3.8 ± 2.9
	Club	5.5 ± 3.2	5.2 ± 4.1	5.4 ± 2.9	4.9 ± 3.4	3.8 ± 2.3	3.7 ± 2.2	5.1 ± 2.8	4.4 ± 2.5
% $Gaze_{ahead}$	Elite	46.3 ± 29.2	59.0 ± 28.8	59.3 ± 30.6	67.7 ± 25.1	32.7 ± 26.1	52.7 ± 18.0	40.2 ± 25.9	46.1 ± 16.9
	Club	43.6 ± 32.5	51.5 ± 23.4	50.0 ± 18.9	54.9 ± 32.8	30.7 ± 20.2	47.6 ± 26.7	40.6 ± 22.7	54.1 ± 21.9
Lateral Gaze-Ball angle	Elite	0.3 ± 0.9	0.4 ± 0.8	0.5 ± 1.1	0.5 ± 0.8	0.6 ± 1.1	0.4 ± 0.8	0.2 ± 0.9	0.2 ± 0.8
	Club	0.5 ± 1.3	0.2 ± 1.2	1.3 ± 1.8	0.0 ± 0.8	0.9 ± 1.2	0.4 ± 1.1	0.0 ± 2.4	0.1 ± 0.9
SD lateral Gaze-Ball angle	Elite	1.7 ± 1.9	1.0 ± 0.5	1.2 ± 0.8	1.3 ± 1.1	1.1 ± 0.7	1.0 ± 0.6	0.9 ± 0.5	0.7 ± 0.3
	Club	2.3 ± 1.4	1.5 ± 1.3	2.4 ± 1.7	1.6 ± 1.9	1.4 ± 1.1	1.1 ± 0.8	2.8 ± 2.6	0.9 ± 0.5
Lateral Gaze-Head angle	Elite	0.1 ± 1.9	0.5 ± 1.4	-0.7 ± 2.4	-0.2 ± 1.3	-0.1 ± 2.2	0.9 ± 2.4	-0.5 ± 2.6	0.0 ± 1.6
	Club	0.3 ± 1.9	0.3 ± 1.4	0.1 ± 2.0	-0.5 ± 1.3	0.3 ± 1.9	0.2 ± 1.5	-0.2 ± 2.3	-0.2 ± 1.7
SD lateral Gaze-Head angle	Elite	2.1 ± 1.2	1.2 ± 0.8	2.2 ± 1.4	1.7 ± 1.0	1.8 ± 1.3	2.0 ± 1.7	2.3 ± 1.6	1.9 ± 1.1
	Club	2.1 ± 1.2	1.5 ± 1.2	2.3 ± 1.2	1.9 ± 1.2	1.6 ± 0.6	1.1 ± 0.9	2.2 ± 1.3	1.8 ± 1.2
Lateral Head-Ball angle	Elite	0.4 ± 1.9	-0.1 ± 1.0	1.1 ± 2.0	0.7 ± 1.5	0.6 ± 1.5	-0.3 ± 1.3	0.8 ± 2.1	0.2 ± 1.4
	Club	0.2 ± 1.4	-0.4 ± 1.0	1.1 ± 0.7	0.9 ± 1.2	0.5 ± 0.9	-0.1 ± 0.8	0.4 ± 1.5	0.6 ± 1.3
SD lateral Head-Ball angle	Elite	1.9 ± 1.8	1.2 ± 0.5	2.4 ± 1.3	2.0 ± 1.1	1.3 ± 0.9	1.3 ± 0.4	1.9 ± 1.3	1.9 ± 1.1
	Club	1.5 ± 0.8	1.4 ± 1.3	2.5 ± 0.9	1.9 ± 1.1	0.9 ± 0.4	0.9 ± 0.5	3.1 ± 2.5	1.5 ± 1.0

Table 4 continued.

Gaze at bat-ball contact									
%BBC$_{contact}$	Elite	9.1 ± 15.0	26.4 ± 23.9	21.5 ± 29.3	26.0 ± 31.2	11.6 ± 15.9	25.0 ± 41.0	12.7 ± 13.3	19.4 ± 22.5
	Club	11.9 ± 26.2	6.0 ± 9.7	7.0 ± 15.0	8.7 ± 16.4	6.7 ± 20.0	4.0 ± 12.7	3.7 ± 11.1	19.2 ± 23.9
%BBC$_{lagging}$	Elite	73.9 ± 20.0	53.0 ± 24.7	46.4 ± 36.4	52.0 ± 28.3	71.9 ± 27.7	68.6 ± 37.7	64.2 ± 33.1	65.4 ± 29.1
	Club	59.8 ± 34.1	86.4 ± 16.0	60.7 ± 38.2	81.8 ± 16.0	84.9 ± 23.7	84.8 ± 32.4	64.2 ± 28.4	66.0 ± 26.7
%BBC$_{Post\text{-}Contact}$	Elite	17.0 ± 19.1	20.6 ± 24.0	32.1 ± 30.4	22.0 ± 20.6	16.5 ± 26.9	6.4 ± 16.0	23.1 ± 37.6	15.2 ± 22.3
	Club	28.3 ± 30.4	7.6 ± 16.2	32.3 ± 33.6	9.5 ± 10.3	8.5 ± 17.0	11.3 ± 31.4	32.1 ± 25.9	14.9 ± 27.8
Type of saccades (%)									
Saccade towards ball-bounce	Elite	48.2 ± 30.0	67.7 ± 26.7	56.5 ± 31.4	64.2 ± 34.1	26.4 ± 29.0	36.7 ± 28.9	39.9 ± 40.5	34.2 ± 30.5
	Club	41.4 ± 50.6	34.5 ± 37.6	58.8 ± 65.5	30.3 ± 27.7	27.5 ± 38.9	22.2 ± 33.3	37.3 ± 45.7	30.2 ± 24.7
Saccade towards bat-ball contact	Elite	1.0 ± 3.5	1.7 ± 5.3	0 ± 0	1.3 ± 4.0	2.4 ± 5.8	8.3 ± 13.6	1.5 ± 5.6	15.1 ± 24.1
	Club	1.7 ± 5.3	0 ± 0	0 ± 0	0 ± 0	5.0 ± 15.8	2.5 ± 7.9	0 ± 0	4.17 ± 9.0
Oblique saccade towards ball-bounce	Elite	7.2 ± 12.8	19.8 ± 27.7	16.7 ± 15.4	12.5 ± 17.1	0.0 ± 0.0	2.5 ± 7.9	5.6 ± 13.8	1.3 ± 4.0
	Club	6.3 ± 15.9	4.0 ± 12.6	23.1 ± 32.6	5.8 ± 9.7	1.7 ± 5.3	2.0 ± 6.3	5.0 ± 15.8	6.7 ± 21.1
Timing of saccade (following ball-release; ms)									
Saccade towards ball-bounce	Elite	414 ± 22	393 ± 26	437 ± 30	417 ± 24	399 ± 38	347 ± 38	399 ± 38	387 ± 24
	Club	407 ± 19	421 ± 23	381 ± 65	373 ± 95	336 ± 41	392 ± 33	375 ± 28	411 ± 30
Saccade towards bat-ball contact	Elite					520 ± 57	440 ± 33		454 ± 19
	Club								460 ± 85
Oblique saccade towards ball-bounce	Elite	430 ± 26	417 ± 37	443 ± 42	440 ± 28			360 ± 57	
	Club	413 ± 19		356 ± 120	400 ± 0				

Figure Captions

Figure 1. Illustration of the experimental set-up and relative angles. Panel (A) illustrates the out-swing (red), straight (yellow) and in-swing (blue) ball trajectories. Note that the location of ball-release, the black hole seen in the ProBatter screen, is offset to the right (from the batter's view point) to simulate natural conditions when batting. Panel (B) shows the three relative angles measured on each trial. Individual angles are subtended by the direction of the head (red), ball (yellow) and gaze (blue) at the batter's eye (in degrees) relative to the direction of ball-release. The relative angles in this case show a positive head-ball angle (head is directed behind the ball), a negative gaze-ball angle (gaze is directed ahead of the ball), and a negative gaze-head angle (gaze is directed ahead of the head direction).

Figure 2. Mean direction of gaze relative to the ball averaged across all batters in each of the four groups when facing the blocked-straight trials. Each graph illustrates (i) the mean vertical gaze and ball angles (red and green lines respectively), and (ii) for each moment in time, the percentage of trials where a saccade to ball-bounce and/or saccade to bat-ball contact was initiated (blue bars). The shaded areas represent the standard deviation across trials, the broken black vertical lines indicate the mean time of ball-bounce, and the solid black lines indicate the mean time of bat-ball contact.

Figure 3. Comparisons of the mean head-ball angle for each of the four groups as a function of ball-length when facing the blocked-straight trials. A positive relative angle indicates that the head is lagging behind the ball. The broken vertical lines represent the mean time of ball-bounce, and the solid lines represent the mean time of bat-ball contact.

Figure 4. Mean differences across ball-lengths for (a) the gaze-head angle as a function of skill level and age; (b) the percentage of trials with a saccade towards bat-ball contact as a function of skill level and ball-length; and (c) the percentage of trials where gaze was directed towards the ball at the moment of bat-ball contact (% $BBC_{contact}$) as a function of skill level and ball-length. Data are displayed with standard error bars.

Figure 5. Saccadic behaviour on individual trials for an exemplar batter from each of the four groups when facing the (A) blocked-straight, and (B) random-straight trials. Each horizontal line represents the time course for a single trial, showing (i) the presence and timing of saccadic eye movements relative to the

moment of ball-release (ms), and (ii) whether gaze was directed towards the ball at the moment of bat-ball contact.

Figure 6. The effects of uncertainty in ball-flight trajectory (blocked-straight vs. random-straight trials) on: (a) the percentage of trials with good bat-ball contact as a function of skill-level; (b) the head-ball angle as a function of ball length; (c) the lateral head-ball angle as a function of ball-length; (d) the timing of the saccade towards ball-bounce as a function of skill-level; (e) the timing of the saccade towards ball-bounce as a function of ball-length; and (f) the percentage of trials with a saccade towards bat-ball contact as a function of ball-length. All data are presented with standard error bars.

Figure 7. Comparisons of the mean (i) gaze-ball, (ii) gaze-head, and (iii) head-ball angles averaged across all batters in each group when hitting random-straight and swinging trials of different ball-lengths. A negative relative angle (e.g., for gaze-ball angle) indicates that the first term (i.e., gaze) is further in advance of the second term (i.e., ball). The broken vertical lines represent the mean time of ball-bounce, and the solid lines represent the mean time of bat-ball contact.

Figure 8. The effect of ball-swing (comparing random-straight vs. swinging trials) as a function of skill-level on (a) the mean gaze-ball angle, and (b) the percentage of trials with an oblique saccade towards ball-bounce. All data are presented with standard error bars.

Figure 9. Mean direction of gaze relative to the ball, averaged across all batters in each of the four groups when facing out-swing and in-swing trials. For each combination of group and ball-length, the figure shows (i) the mean vertical gaze and ball angles (red and green lines respectively), and (ii) for each moment in time, the percentage of trials where a saccade to ball-bounce and/or saccade to bat-ball contact was initiated (blue bars). The shaded areas represent the standard deviation across trials, the broken black vertical lines indicate the mean time of ball-bounce, and the solid black lines indicate the mean time of bat-ball contact.

Figure 1

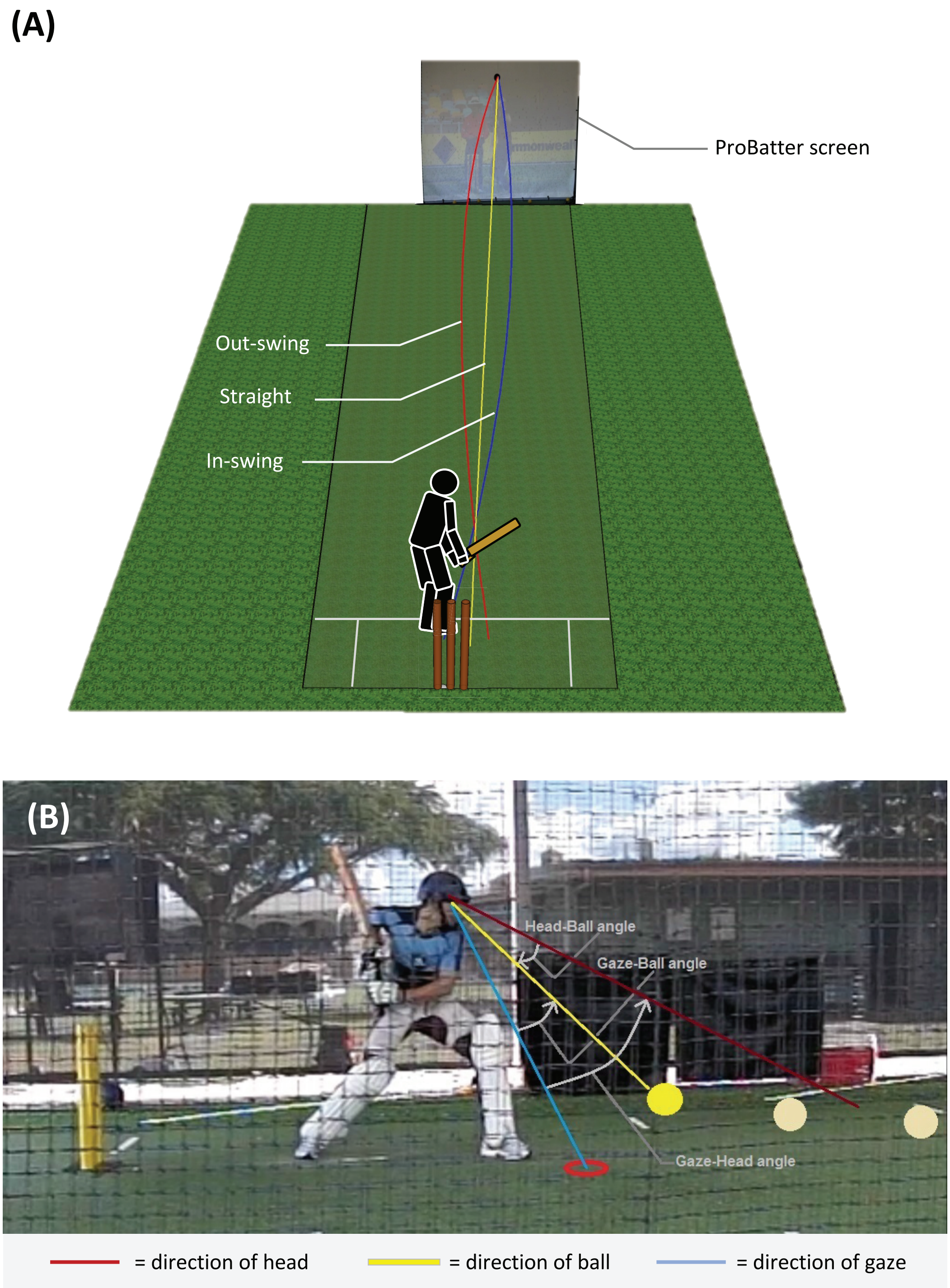
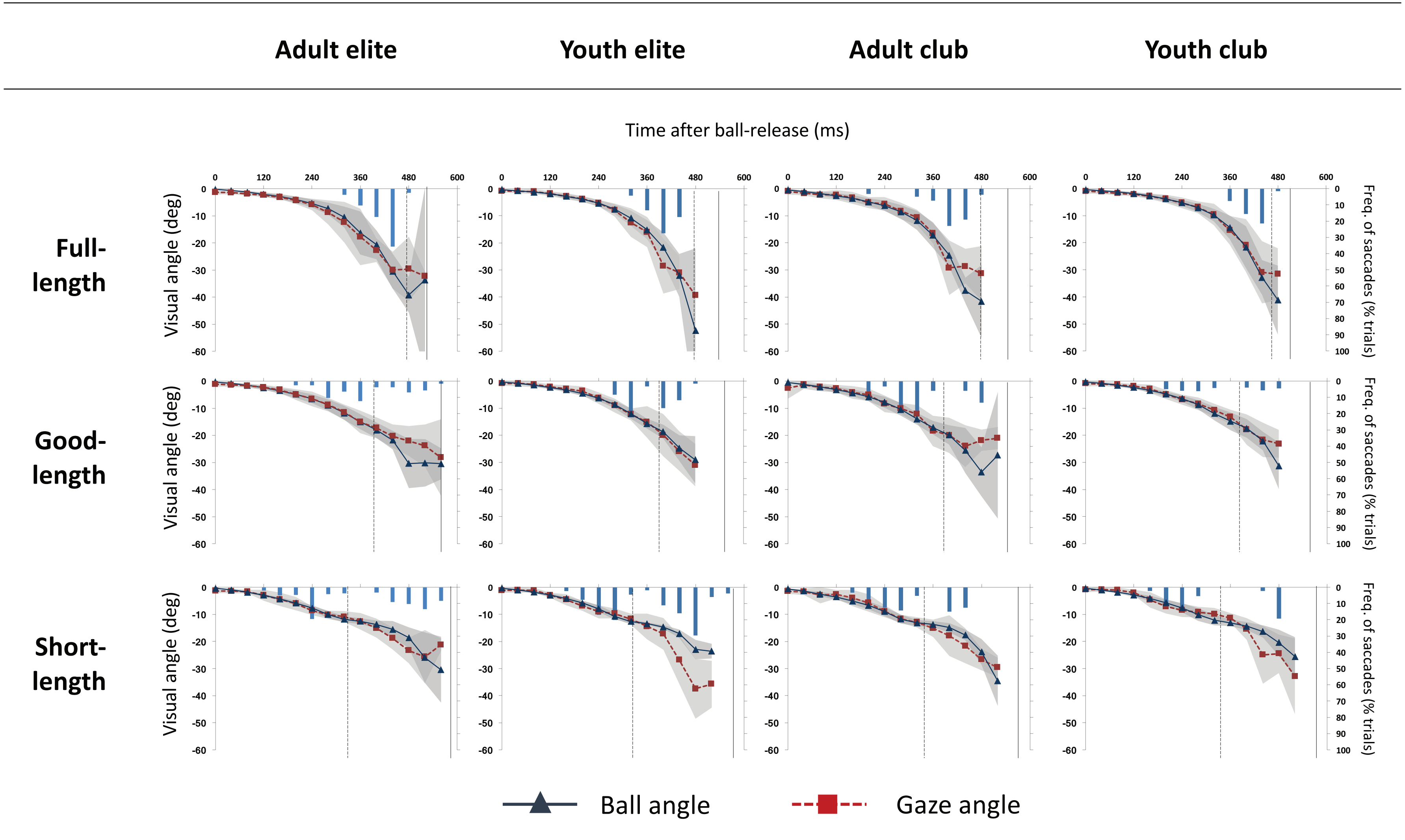

(A)
ProBatter screen
Out-swing
Straight
In-swing
(B)
Head-Ball angle
Gaze-Ball angle
Gaze-Head angle
= direction of head
= direction of ball
= direction of gaze

Figure 2



Adult elite
Youth elite
Adult club
Youth club
Time after ball-release (ms)
Full-length
Good-length
Short-length
Visual angle (deg)
Freq. of saccades (% trials)
Ball angle
Gaze angle

Figure 3

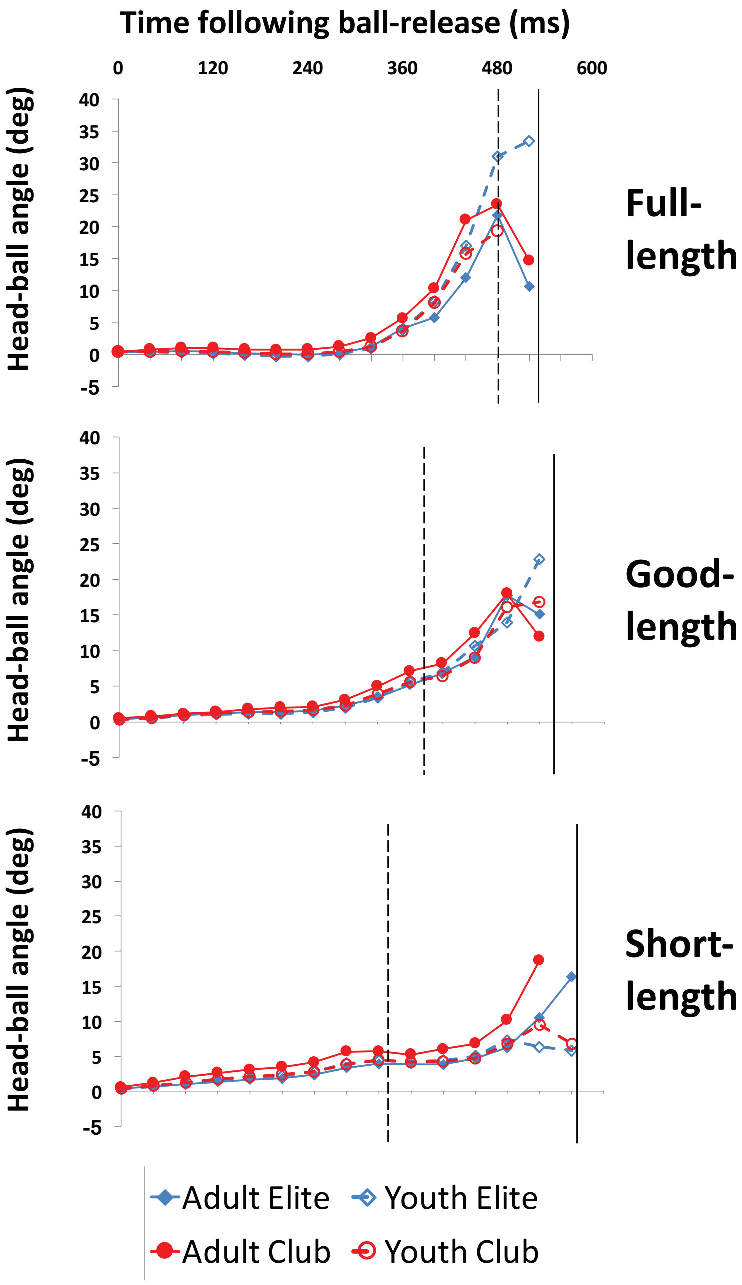
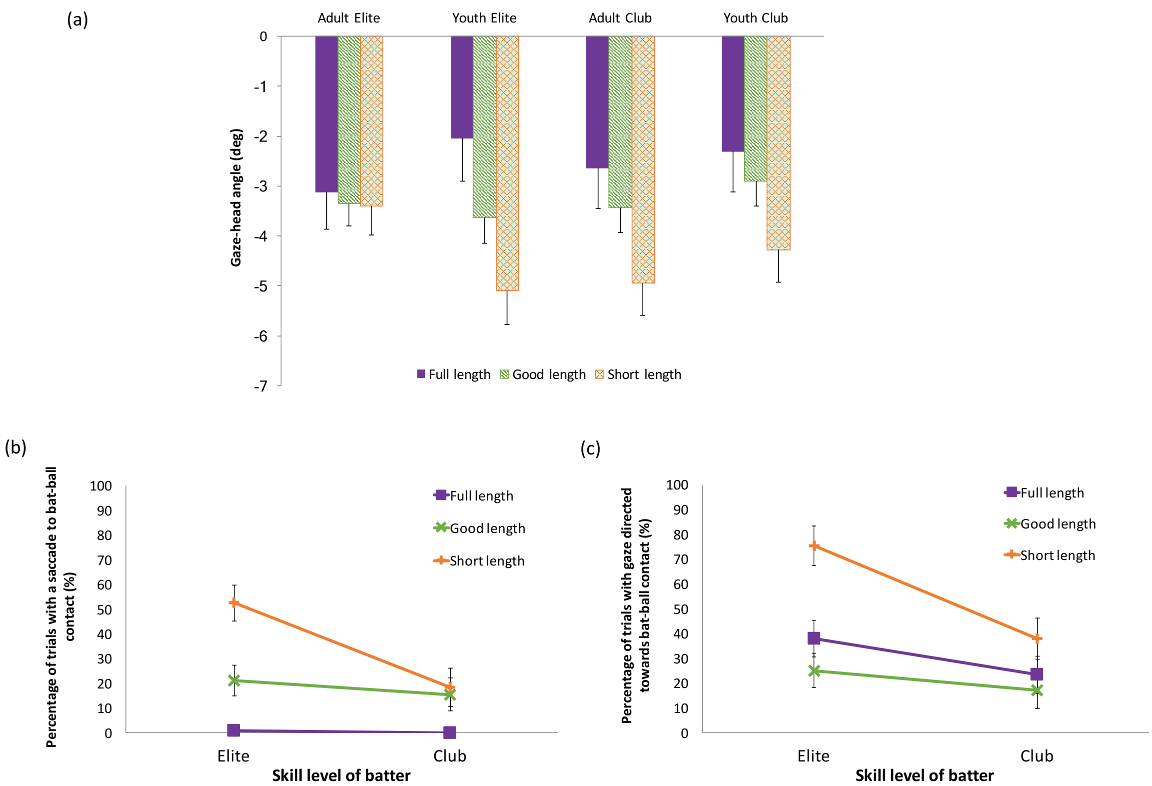
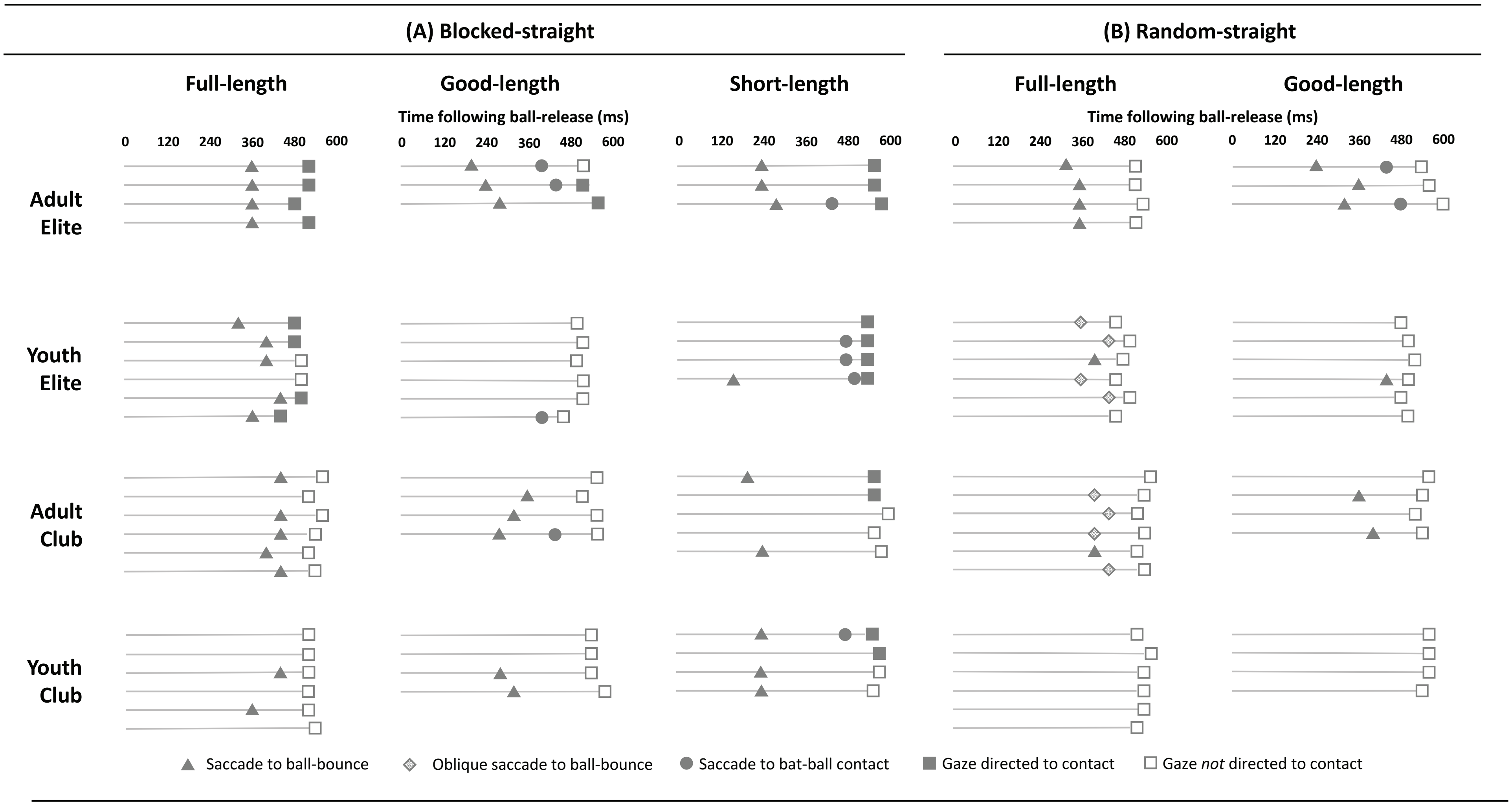

Time following ball-release (ms)
0
120
240
360
480
600
Head-ball angle (deg)
40
35
30
25
20
15
10
5
0
-5
Full-length
Head-ball angle (deg)
40
35
30
25
20
15
10
5
0
-5
Good-length
Head-ball angle (deg)
40
35
30
25
20
15
10
5
0
-5
Short-length
Adult Elite
Youth Elite
Adult Club
Youth Club

Figure 4



(a)
Adult Elite
Youth Elite
Adult Club
Youth Club
0
-1
-2
-3
-4
-5
-6
-7
Gaze-head angle (deg)
Full length
Good length
Short length
(b)
100
90
80
70
60
50
40
30
20
10
0
Percentage of trials with a saccade to bat-ball contact (%)
Full length
Good length
Short length
Elite
Club
Skill level of batter
(c)
100
90
80
70
60
50
40
30
20
10
0
Percentage of trials with gaze directed towards bat-ball contact (%)
Full length
Good length
Short length
Elite
Club
Skill level of batter

Figure 5



(A) Blocked-straight
(B) Random-straight
Full-length
Good-length
Short-length
Full-length
Good-length
Time following ball-release (ms)
Time following ball-release (ms)
0 120 240 360 480 600
Adult Elite
Youth Elite
Adult Club
Youth Club
Saccade to ball-bounce
Oblique saccade to ball-bounce
Saccade to bat-ball contact
Gaze directed to contact
Gaze *not* directed to contact

Figure *6*

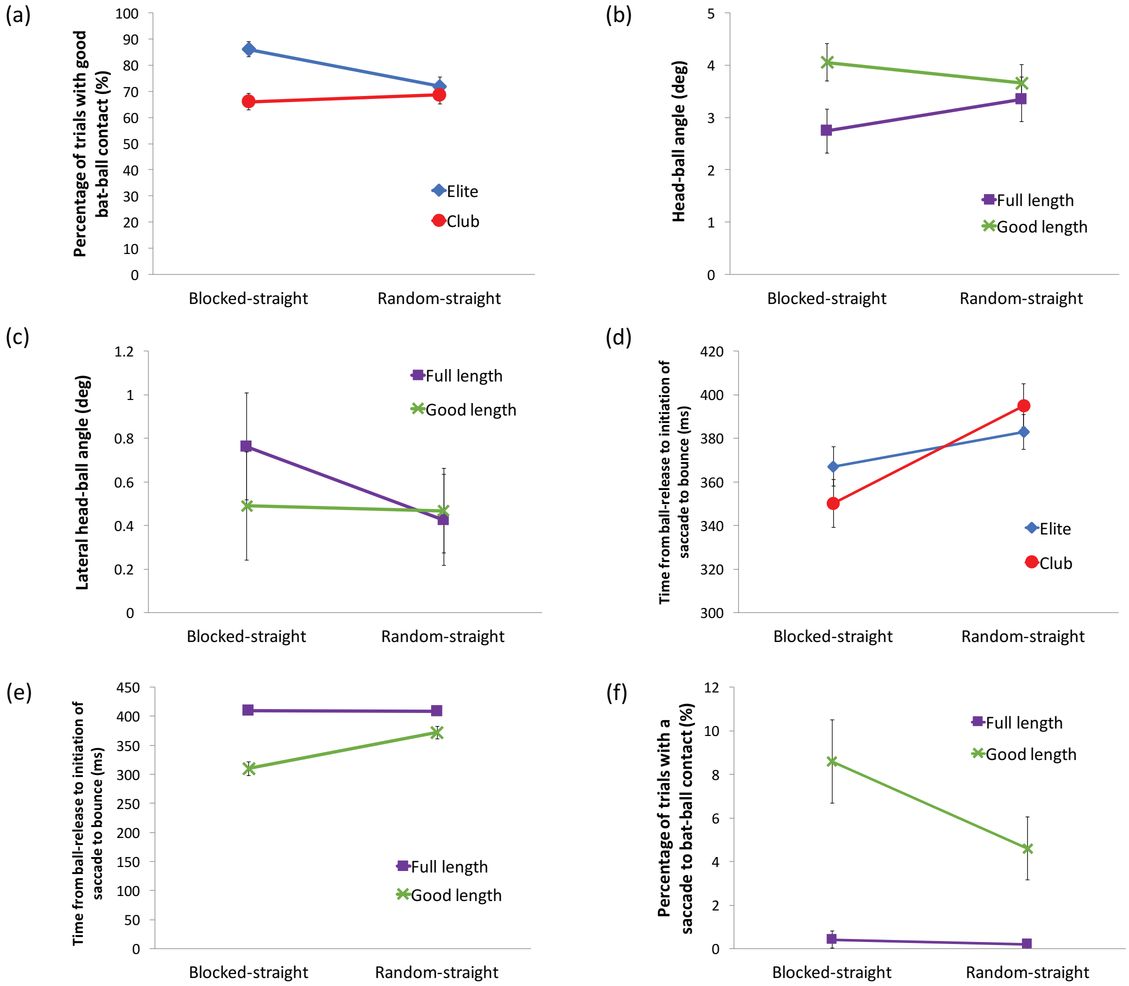

(a)
Percentage of trials with good bat-ball contact (%)
100
90
80
70
60
50
40
30
20
10
0
Elite
Club
Blocked-straight
Random-straight
(b)
Head-ball angle (deg)
5
4
3
2
1
0
Full length
Good length
Blocked-straight
Random-straight
(c)
Lateral head-ball angle (deg)
1.2
1
0.8
0.6
0.4
0.2
0
Full length
Good length
Blocked-straight
Random-straight
(d)
Time from ball-release to initiation of saccade to bounce (ms)
420
400
380
360
340
320
300
Elite
Club
Blocked-straight
Random-straight
(e)
Time from ball-release to initiation of saccade to bounce (ms)
450
400
350
300
250
200
150
100
50
0
Full length
Good length
Blocked-straight
Random-straight
(f)
Percentage of trials with a saccade to bat-ball contact (%)
12
10
8
6
4
2
0
Full length
Good length
Blocked-straight
Random-straight

Figure 7

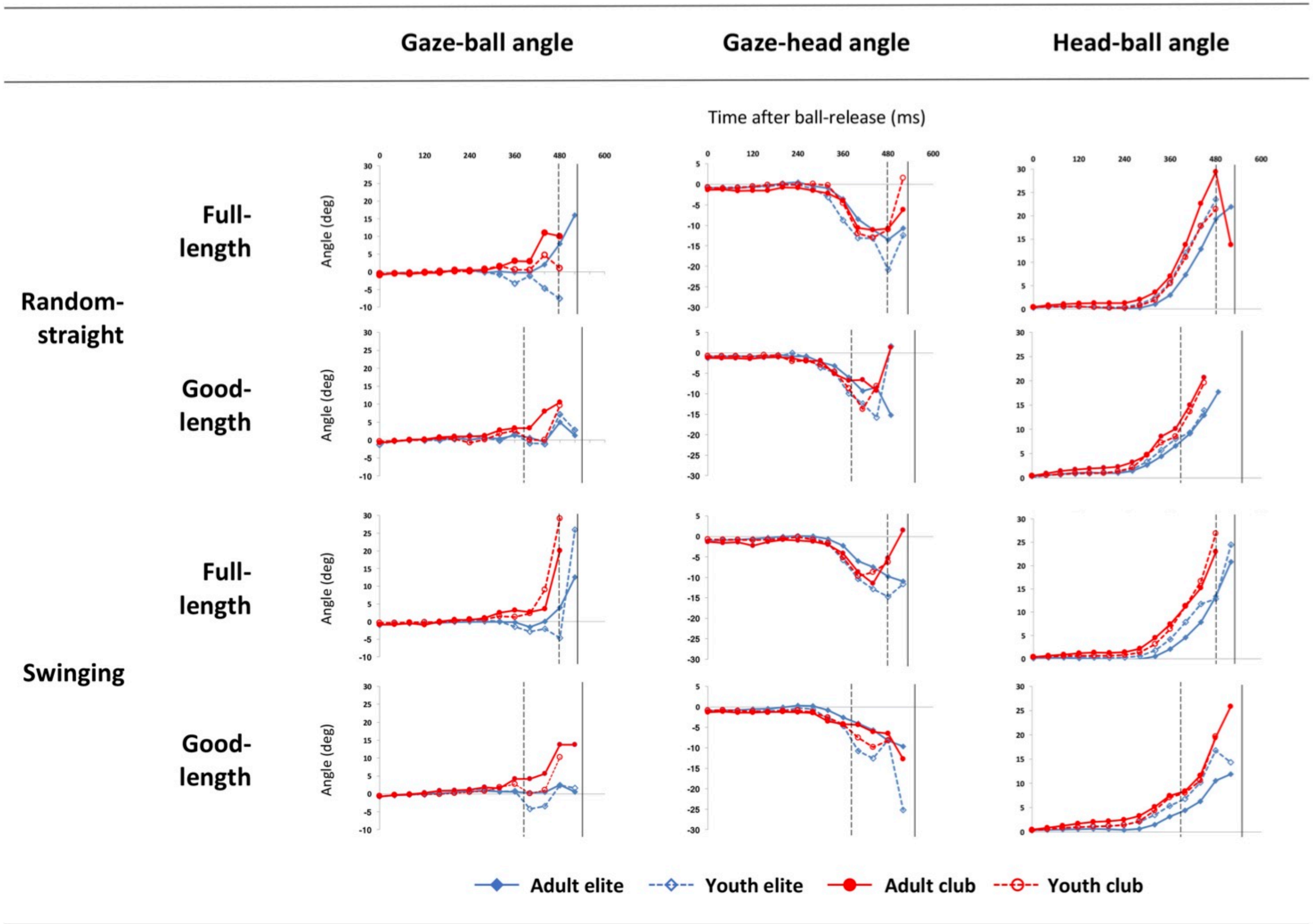

Gaze-ball angle
Gaze-head angle
Head-ball angle
Time after ball-release (ms)
Random-straight
Full-length
Good-length
Swinging
Full-length
Good-length
Angle (deg)
Adult elite
Youth elite
Adult club
Youth club

Figure 8

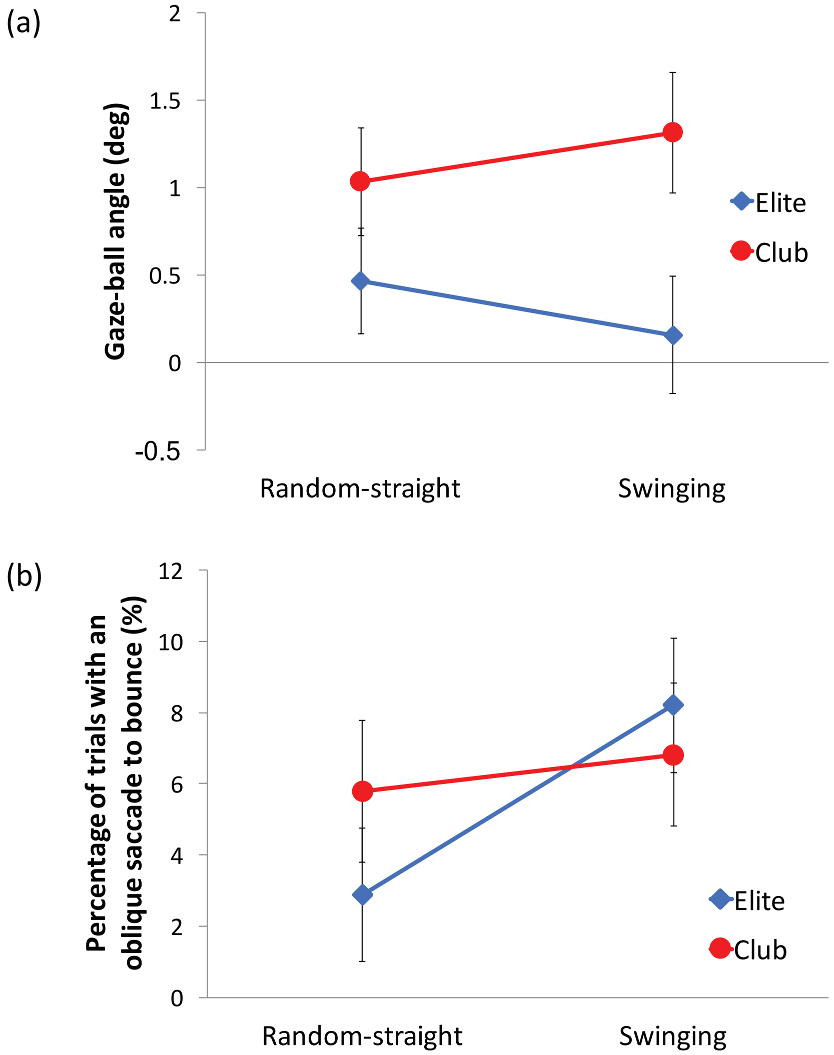
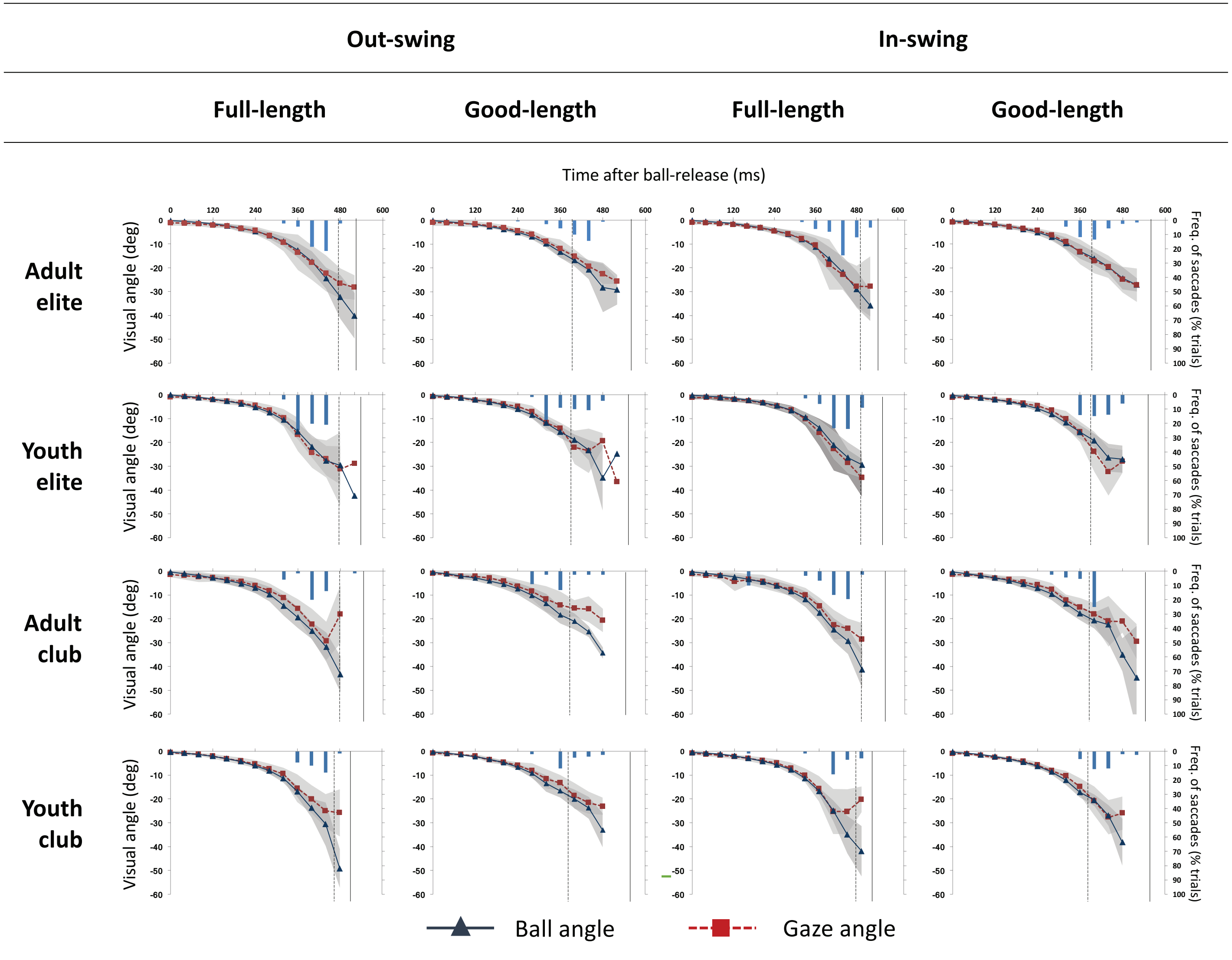

(a)
Gaze-ball angle (deg)
2
1.5
1
0.5
0
-0.5
Elite
Club
Random-straight
Swinging
(b)
Percentage of trials with an oblique saccade to bounce (%)
12
10
8
6
4
2
0
Elite
Club
Random-straight
Swinging

Figure 9


Out-swing
In-swing
Full-length
Good-length
Full-length
Good-length
Time after ball-release (ms)
Adult elite
Youth elite
Adult club
Youth club
Visual angle (deg)
Freq. of saccades (% trials)
Ball angle
Gaze angle